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ABSTRACT

This student manual is designed to accompany a four and one half day course in isokinetic air pollution source sampling. Covered in the manual under chapter headings are: (1) basic definitions; (2) basic concepts of gases; (3) United States EPA methods sampling train; (4) calibration procedures; (5) source testing; (6) source sampling calibrations; (7) report writing; (8) error analysis; and (9) additional topics. Assorted appendices are provided. (RE)

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Course 450
Source Sampling for Particulate Pollutants

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Student Manual

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AIR POLLUTION TRAINING INSTITUTE
MANPOWER AND TECHNICAL INFORMATION BRANCH
CONTROL PROGRAMS DEVELOPMENT DIVISION
OFFICE OF AIR QUALITY PLANNING AND STANDARDS

The Air Pollution Training Institute (1) conducts training for personnel working on the development and improvement of state, and local governmental, and EPA air pollution control programs, as well as for personnel in industry and academic institutions; (2) provides consultation and other training assistance to governmental agencies, educational institutions, industrial organizations, and others engaged in air pollution training activities; and (3) promotes the development and improvement of air pollution training programs in educational institutions and state, regional, and local governmental air pollution control agencies. Much of the program is now conducted by an on-site contractor, Northrop Services, Inc.

One of the principal mechanisms utilized to meet the Institute's goals is the intensive short term technical training course. A full-time professional staff is responsible for the design, development, and presentation of these courses. In addition the services of scientists, engineers, and specialists from other EPA programs governmental agencies, industries, and universities are used to augment and reinforce the Institute staff in the development and presentation of technical material.

Individual course objectives and desired learning outcomes are delineated to meet specific program needs through training. Subject matter areas covered include air pollution source studies, atmospheric dispersion, and air quality management. These courses are presented in the Institute's resident classrooms and laboratories and at various field locations.

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Preface

This manual is to be used in conjunction with the lectures and laboratory presented in Course 450 of the Air Pollution Training Institute. A student workbook accompanies these materials.

Portions of this manual may become obsolete as regulations and methods change. Since the field of air pollution measurement progresses rapidly, efforts should be made by the student to keep abreast of new developments by attending EPA workshops and supplementing the material in this manual with information from the current literature.

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Introduction to Source Sampling

The Clean Air Act was enacted to protect the quality of the nation's air resources. It initiated research and development programs to monitor and control pollutants emitted to the atmosphere. Emissions from stationary sources are monitored under the statutes of the act.

Stationary source sampling is the experimental process for evaluating the characteristics of industrial waste gas stream emissions into the atmosphere. Materials emitted to the air from these sources can be solid, liquid, or gas; organic or inorganic. The effluent pollutants emitted to the atmosphere from a source may contain many different pollutant materials. The quantity and type of each pollutant must be known so a control strategy can be formed. The procedures outlined in the *Code of Federal Regulations,* Methods 1-5 for isokinetic stationary source sampling are a versatile system for evaluating these emissions.

The isokinetic source sampling procedures written in the *Code of Federal Regulations* give the environmental and industrial engineer a great deal of data on the operation of an individual process. The sampling system measures a number of variables at the source while extracting from the gas stream a sample of known volume. The information on source parameters in conjunction with quantitative and qualitative laboratory analysis of the extracted sample makes possible calculation of the total amount of pollutant material entering the atmosphere. These data are important for controlling pollutant emissions, evaluating source compliance with regulations or providing information upon which control regulations will be based. The industry performing source sampling gains information on the operation of the process tested. The sampling of source emissions gives valuable process data which can be used to evaluate process economics and operation control. Information gathered during a source test experiment may also be used for determining existing control device efficiency or for designing new process and emissions control equipment.

Isokinetic source sampling provides a great deal of important data on the operating parameters and emissions of an industrial stationary source. This information is used as the basis for decisions on a variety of issues. The data taken during a source test experiment must, therefore, be a precise representation of the source emissions. This task requires a thorough knowledge of the recommended sampling procedures in conjunction with an understanding of process operations. The typical industrial process may vary conditions at the source for a variety of economic or logistical reasons. The source sampling experiment must be designed to prevent process variation from biasing the source sample. The test engineer has the additional problems of carrying out an important experiment under extremely difficult working conditions. These problems make source testing an endeavor that should be performed only by trained personnel.

The Air Pollution Training Institute has assembled the materials contained in this manual to assist the engineer and technician involved in performing source test experiments. The manual presents the theoretical evolution of the isokinetic methods and practical step-by-step descriptions of the application of these methods. The equipment used is diagrammed and operations are thoroughly explained. The Air Pollution Training Institute Course 450 laboratory, lectures, and classroom workbook—in conjunction with the materials contained in this manual—represent a comprehensive training experience in source sampling with EPA Method 5 procedures.

Chapter 1

Basic Definitions

SOURCE SAMPLING FOR PARTICULATE EMISSIONS:

Source sampling methods are used to determine emission compliance with regulatory statutes. Source testing provides data on the pollutant emission rate. Test data are also used to evaluate best available control technology.

ISOKINETIC SOURCE SAMPLING

Webster's dictionary defines *iso* as denoting equality, similarity, uniformity. *Kinetic* is defined as of, pertaining to, or due to motion. Isokinetic sampling is an equal or uniform sampling of particles and gases in motion within the stack.

Isokinetic source sampling is achieved when the velocity of gas entering the sampling nozzle is exactly equal to the velocity of the approaching gas stream. This provides a uniform, unbiased sample of the pollutants being emitted by the source. Isokinetic source sampling most closely evaluates and defines various parameters in the stack as they actually exist at the time of sampling.

MOISTURE CONTENT OF A STACK GAS

The moisture content of a stack gas is the percentage of water vapor present calculated on a volume basis. The moisture content of the stack is important in calculating the apparent molecular weight of the stack gas, which must be known for application of the ideal gas law. The ideal gas law defines the relationship between pressure, volume, temperature, and mass of a "perfect" gas.

MOLE FRACTION OF A GAS

At standard temperature and pressure (32°F and 29.92 in. Hg.) a mole of gas fills 22.4 liters. The ratio of the number of moles of the component gas to the number of moles in the whole mixture is equal to the component's mole fraction. The mole fraction of each constituent of a gas mixture must be known for calculation of the apparent molecular weight of the mixture. This is done on a volume basis.

MOLECULAR WEIGHT OF A STACK GAS

The molecular weight of a stack gas is equal to the sum of the mole fraction of each constituent multiplied by the molecular weight of that constituent.

(Eq.1-1)

$$M_{mix} = \Sigma B_x M_x$$

M_{mix} = *apparent molecular weight of stack gas mixture*
M_x = *molecular weight of individual constituent*
B_x = *mole fraction of constituent gas*

The apparent molecular weight of the stack gas is important for application of the ideal gas law.

IDEAL GAS LAW

The ideal gas law defines the relationships among pressure, volume, temperature, and mass of any gas.

(Eq.1-2)

$$PV = \frac{mRT}{M}$$

where
P = *absolute pressure*
V = *volume of a gas*
m = *mass of a gas*
M = *molecular weight of a gas*
T = *absolute temperature (°K or °R)*
R = *universal gas constant (units consistent with others used in the equation)*

ABSOLUTE TEMPERATURE

Temperature is a mass independent property related to the average kinetic energy in a system due to molecular motion. Heat is a mass dependent property of the system's total kinetic energy of molecular motion. The flow of heat in or out of a system is determined by measuring changes in the temperature of the system. Temperature is a factor in identifying the state of a gas system as defined by the ideal gas law. Absolute temperature measure is given in °Kelvin (°C + 273.16) or °Rankine (°F + 459.67).

ABSOLUTE PRESSURE

Fluids are subject only to shear and compression stress. Pressure is compression stress expressed as the force applied per unit area.

Absolute pressure is "absolute zero pressure," the sum of the atmospheric pressure and any gage pressure above or below atmospheric:

(Eq.1-3)

$$P = P_b + p_g$$

where
P = *absolute pressure*
P_b = *barometric pressure (atmospheric)*
p_g = *gage pressure (pressure measured by a gage, higher or lower than atmospheric pressure)*

PITOT TUBE

The pitot tube is a simple device used to measure the velocity of a fluid flowing in an open channel. The complexity of underlying fluid flow principles of pitot tube gas velocity measurement are not apparent in the simple operation of this device. It should, however, be considered and treated as a sophisticated instrument.

The pitot tube actually measures the velocity pressure of a gas stream (Figure 1-1). Gas streamlines, approaching a round object placed in a duct, flow around the object except at point "P_+." Here the gas stagnates, and the total pressure is found. The difference between this total pressure and the static pressure (p_s) is the velocity pressure (Δp).

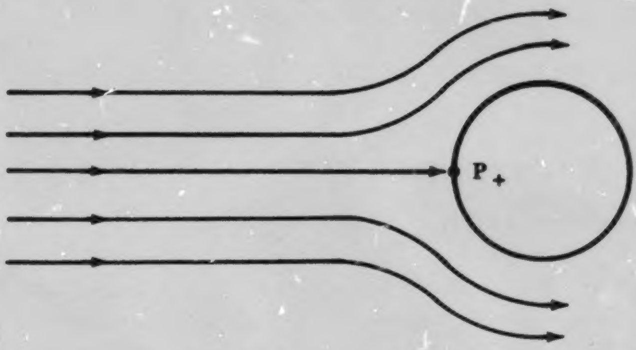

Figure 1-1. Gas stagnation against an object.

The static pressure in a gas stream is defined as the pressure that would be indicated by a pressure gage if it were moving along with the stream so as to be at rest or be relatively "static" with respect to the fluid.

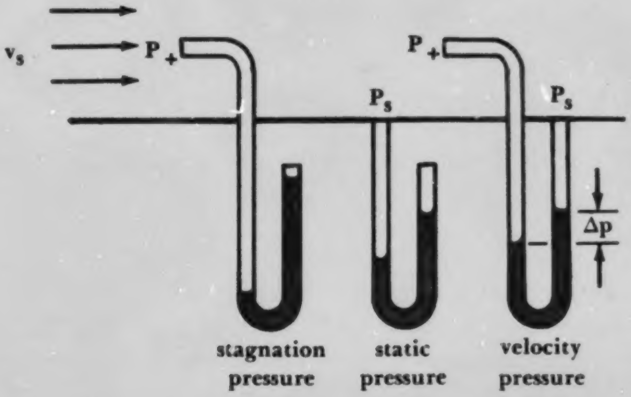

Figure 1-2. Components of total pressure.

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Bernoulli's Equation relates pitot tube velocity pressure to gas velocity in the equation:

(Eq.1-4)

$$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}}$$

where

v_s = *velocity of the stack gas*
K_p = *dimensional constant*
C_p = *pitot tube calibration coefficient*
T_s = *absolute temperature of the gas*
P_s = *absolute pressure of stack gas*
M_s = *apparent molecular weight of stack gas*

This equation is derived in the appendixes.

DRY GAS METER CORRECTION FACTOR

The term "primary standard" is a theoretical expression. It implies absolute measurement of a given variable. This is not possible in actual practice. We, therefore, "designate" standards of measurement. The spirometer is the designated standard for gas volume measurement. A volume measurement made by any device other than a spirometer should be corrected to correspond with spirometer readings. Volume readings made by the sampling train meter console dry gas meter are correlated to spirometer volume by a correction factor. This factor is determined empirically prior to using the meter in field work:

(Eq.1-5)

$$DGMCF = \frac{SV}{DGMV}$$

where

DGMCF = *dry gas meter correction factor*
SV = *spirometer volume*
DGMV = *dry gas meter volume*

The DGMCF is then applied to correct volumes measured by the dry gas meter:

(Eq.1-6) $DGMV \times DGMCF$ = *volume corrected to spirometer reading*

ORIFICE METER

The simplest and most familiar type of orifice meter is a circular hole in a thin flat plate held between flanges at a joint in a pipe (Figure 1-3). The plate is located 8 diameters upstream and 2 diameters downstream of any flow disturbance, perpendicular to the pipe axis with the hole concentric to the pipe.

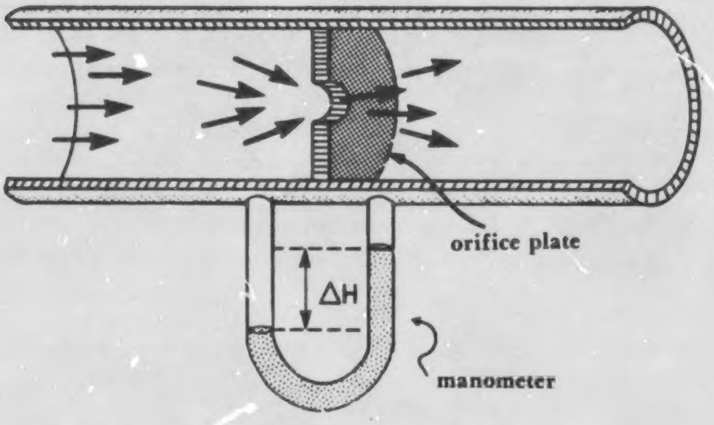


Figure 1-3. Simple orifice meter.

The orifice creates a pressure differential between the two sides of the plate. This pressure differential is related to the flow rate of gas through the orifice device:

(Eq.1-7)

$$Q_m = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}}$$

where Q_m = *volumetric gas flow rate*
ΔH = *pressure differential across the orifice*
T_m = *absolute gas temperature (°R or °K)*
P_m = *absolute pressure (barometric) inches Hg or mm Hg*
K_m = *proportionality factor determined by empirical calibration*

ΔH

A term designated to describe the manometer setting (pressure differential across the orifice) of a calibrated orifice meter. During calibration of the orifice meter, ΔH defines a given flow rate through the meter. In field use, the nomograph is used to calculate a desired ΔH, which correlates flow through the meter to the velocity of gas entering the sampling nozzle. Gas velocity at the sampling nozzle is thus indirectly determined by flow rate.

NOMOGRAPH

The stack sampling nomograph is essentially a slide rule. The nomograph solves the isokinetic equation for EPA Method 5 sampling train. The flow rate through the sampling train can then be adjusted to correspond to the stack gas velocity.

$\Delta H_{@}$

A designated term used to describe the orifice meter manometer setting that will allow 0.75 cubic feet/minute of dry air at 68°F and 29.92 in. of Hg to flow through the meter. A condensed mathematical definition is given as:

(Eq.1-8)

$$\Delta H_{@} = \frac{0.9244}{K_m^2}$$

where 0.9244 = *a constant for conditions and units defined*
K_m = *orifice meter calibration factor (see orifice meter)*

Nomenclature

A_n — sampling nozzle cross-sectional area
A_s — stack cross-sectional area
a — mean particle projected area
B_{wm} — percent moisture present in gas at meter
B_{ws} — percent moisture present in stack gas
C_p — pitot tube calibration coefficient
$C_{p(std)}$ — standard pitot-static tube calibration coefficient
c_s — particulate concentration in stack gas mass/volume
c_{ws} — particulate concentration on a wet basis mass/wet volume
$c_{s_{12}}$ — particulate concentration corrected to 12% CO_2
$c_{s_{50}}$ — particulate concentration corrected to 50% excess air

D_E — equivalent diameter
D_H — hydraulic diameter
D_n — source sampling nozzle diameter
E — emission rate mass/heat Btu input
e — base of natural logarithms (1n10 = 2.302585)
%EA — percent excess air
F_c — F-factor using c_s and CO_2 on wet or dry basis
F_d — F-factor using c_s and O_2 on a dry basis
F_w — F-factor using c_{ws} and O_2 on a wet basis
F_o — miscellaneous F-factor for checking orsat data
$\Delta H_@$ — pressure drop across orifice meter for 0.75 CFM flow rate at standard conditions
ΔH — pressure drop across orifice meter
j — equal area centroid
K_p — pitot tube equation dimensional constant

$$\text{Metric Units} = 34.97 \text{ m/sec.} \left[\frac{\text{g/g-mole (mmHg)}}{(^\circ\text{K})(\text{mm } H_2O)}\right]^{1/2}$$

$$\text{English Units} = 85.49 \text{ ft./sec.} \left[\frac{\text{lb/lb-mole(in. Hg)}}{(^\circ\text{R})(\text{in. } H_2O)}\right]^{1/2}$$

L — length of duct cross-section at sampling site
ℓ — path length
L_1 — plume exit diameter
L_2 — stack diameter
m — mass
M_d — dry stack gas molecular weight
M_s — wet stack gas molecular weight
n — number of particles
N_{Re} — Reynolds number
O_1 — plume opacity at exit
O_2 — in stack plume opacity
P_{atm} — atmospheric pressure
P_b — barometric pressure ($P_b = P_{atm}$)
P_m — absolute pressure at the meter
pmr — Pollutant mass rate
P_s — absolute pressure in the stack
P_{std} — standard absolute pressure
Metric Units = 760 mm Hg
English Units = 29.92 in. Hg
Δp — gas velocity pressure
$\Delta p_{(std)}$ — standard velocity pressure read by the standard pitot tube
Δp_{test} — gas velocity pressure read by the type "S" pitot tube
q — particle extinction coefficient
Q_s — stack gas volumetric flow rate corrected to standard conditions

R — Gas law constant, $21.83 \dfrac{(\text{in. Hg})(\text{ft.}^3)}{(\text{lb} - \text{mole})(°\text{R})}$

t — temperature (°Fahrenheit or °Celsius)
T_m — absolute temperature at the meter
Metric Units = °C + 273 = °K
English Units = °F + 460 = °R
T_s — absolute temperature of stack gas
T_{std} — standard absolute temperature
Metric Units = °20°C + 273 = 293°K
English Units = 68°F + 460 = 528°R
V_m — volume metered at actual conditions
$V_{m_{std}}$ — volume metered corrected to standard conditions
v.p. — water vapor pressure
v_s — stack gas velocity
Volume H_2O — Metric units = 0.00134 m^3/ml × ml H_2O
English units = 0.0472 $ft.^3$/ml × ml H_2O
W — width of the duct cross-section at the sampling site
θ — time in minutes

Subscripts

atm — atmospheric
ave — average
b — barometric
d — dry gas basis
f — final
g — gage
i — initial
m — at meter
n — at nozzle
p — of pitot tube
s — at stack
SCF — standard cubic feet
std — standard conditions
w — wet basis

Chapter 2

Basic Concepts of Gases

EXPRESSION OF GAS TEMPERATURE

The Fahrenheit and Celsius Scales

The range of units on the Fahrenheit scale between freezing and boiling is 180; on the Celsius or Centigrade scale, the range is 100. Therefore, each Celsius-degree is equal to 9/5 or 1.8 Fahrenheit-degree. The following relationships convert one scale to the other:

(Eq.2-1) $$°F = 1.8\ °C + 32$$

(Eq.2-2) $$°C = (°F - 32)/1.8$$

where °F = *degrees Fahrenheit*
°C = *degrees Celsius or degrees Centigrade*

Absolute Temperature

Experiments with perfect gases have shown that, under constant pressure, for each change in Fahrenheit-degree below 32 °F the volume of gas changes 1/491.67. Similarly, for each Celsius degree, the volume changes 1/273.16. Therefore, if this change in volume per temperature-degree is constant, the volume of gas would, theoretically, become zero at 491.67 Fahrenheit degrees below 32 °F or at a reading of − 459.67 °F. On the Celsius or Centigrade scale, this condition occurs at 273.16 Celsius-degrees below 0 °C, or at a temperature of − 273.16 °C.

Absolute temperatures determined by using Fahrenheit units are expressed as degrees Rankine (°R); those determined by using Celsius units are expressed as degrees Kelvin (°K). The following relationships convert one scale to the other:

(Eq.2-3) $$°R = °F + 459.67$$

(Eq.2-4) $$°K = °C + 273.16$$

The symbol T will be used in this outline to denote absolute temperature and t will be used to indicate Fahrenheit or Celsius degrees.

EXPRESSION OF GAS PRESSURE

Definition of Pressure

A body may be subjected to three kinds of stress: shear, compression, and tension. Fluids are unable to withstand tensile stress; hence, they are subject to shear and compression only.

Unit compressive stress in a fluid is termed pressure and is expressed as force per unit area (e.g., lb/in.^{2} or psi, Newtons/m^2 or Pa).

Pressure is equal in all directions at a point within a volume of fluid, and acts perpendicular to a surface.

Barometric Pressure

Barometric pressure and atmospheric pressure are synonymous. These pressures are measured with a barometer and are usually expressed as inches, or millimeters, of mercury (Hg). Standard barometric pressure is the average atmospheric pressure at sea level, 45° north latitude at 35°F. It is equivalent to a pressure of 14.696 pounds-force per square inch exerted at the base of a column of mercury 29.92 inches high. Weather and altitude are responsible for barometric pressure variations.

Gage Pressure

Measurements of pressure by ordinary gages are indications of difference in pressure above, or below, that of the atmosphere surrounding the gage. Gage pressure, then, is ordinarily the pressure of the system. If greater than the pressure prevailing in the atmosphere, the gage pressure is expressed as a positive value; if smaller, the gage pressure is expressed as negative. The term, *vacuum*, designates a negative gage pressure.

The abbreviation *g* is used to specify a gage pressure. For example, psig, means pounds-force per square inch gage pressure.

Absolute Pressure

Because gage pressure (which may be either positive or negative) is the pressure relative to the prevailing atmospheric pressure, the gage pressure, added algebraically to the prevailing atmospheric pressure (which is always positive), provides a value that has a datum of *absolute zero pressure*. A pressure calculated in this manner is called absolute pressure. The mathematical expression is:

(Eq. 2-5)

$$P = P_b + p_g$$

where

P = *absolute pressure*
P_b = *barometric pressure (atmospheric)*
p_g = *gage pressure*

The abbreviation, *a*, is sometimes used to indicate that the pressure is absolute. For example, psia, means pounds per square inch absolute pressure. The symbol P by itself, will also be used in this manual to indicate absolute pressure.

The absolute pressure allows conversion of one pressure system to the other. Relationship of the pressure systems are shown graphically in Figure 2-1 using two typical gage pressures, (1) and (2). Gage pressure (1) is above the zero from which gage pressures are measured, and, hence, is expressed as a positive value; gage pressure (2) is below the gage pressure zero, and, therefore, is expressed as a negative value.

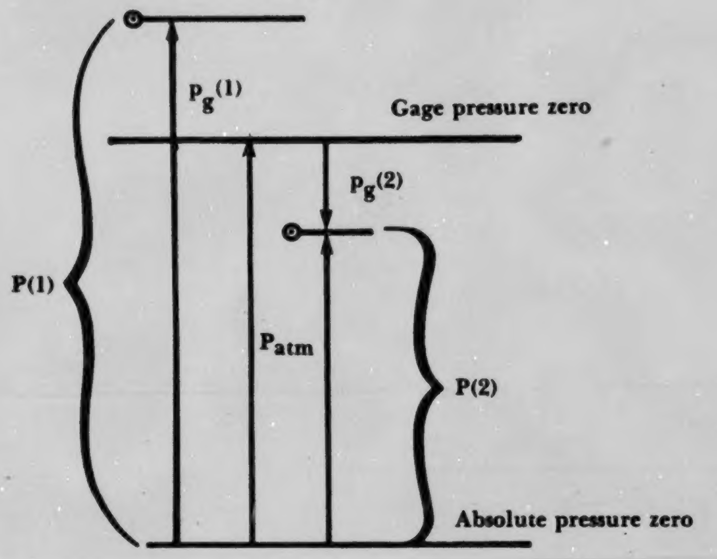


Figure 2-1. Gas-pressure relationship.

Dalton's Law of Partial Pressure

When gases, or vapors (having no chemical interaction), are present as a mixture in a given space, the pressure exerted by a component of the gas mixture at a given temperature is the same as it would exert if it filled the whole space alone. The pressure exerted by one component of a gas mixture is called its partial pressure. The total pressure of the gas mixture is the sum of the partial pressures.

THE LAW OF IDEAL GASES

The Laws of Boyle and Charles

Boyle's Law states that, when the temperature *(T)* is held constant, the volume *(V)* of a given mass of a perfect gas of a given composition varies inversely as the absolute pressure, i.e.:

$$V \propto \frac{1}{P} \text{ at constant } T$$

where $\propto$ = *proportional to*

Charles' Law states that, when the volume is held constant, the absolute pressure of a given mass of a perfect gas of a given composition varies directly as the absolute temperature, i.e.: $P \propto T$ at constant volume.

The Law of Ideal Gases

Both Boyle's and Charles' Law are satisfied in the following equation:

(Eq.2-6)

$$PV = \frac{mRT}{M}$$

where

P = *absolute pressure*
V = *volume of a gas*
m = *mass of gas*
M = *molecular weight of a gas*
T = *absolute temperature*
R = *universal gas constant*

The unit of R depends upon the units of measurement used in the equation. Some useful values are:

(1) $1544 \, \frac{(lb)\,(ft)}{(lb\text{-}mole)(°R)}$

(2) $21.83 \, \frac{(in.\ Hg)\,(ft^3)}{(lb\text{-}mole)(°R)}$

(3) $554.6 \, \frac{(mm\ Hg)\,(ft^3)}{(lb\text{-}mole)(°R)}$

(4) $82.06 \, \frac{(cm^3)\,(atm)}{(gm\text{-}mole)(°K)}$

In the above units of R:

$V = ft^3$, *cm^2 for (4)*
$m = lb$, *g for (4)*
$M = lb/lb\text{-}mole$, *g/g-mole for (4)*
$T = °R$, *°K for (4)*
$P = lb/ft^2$ *for (1)*
= *in. Hg for (2)*
= *mm Hg for (3)*
= *atm for (4)*

Any value of R can be obtained by utilizing the fact, with appropriate conversion factors, that there are 22.414 liters per gm-mole or 359 ft.^{3} per lb-mole at 32°F and 29.92 in. Hg.

CALCULATION OF APPARENT MOLECULAR WEIGHT OF GAS MIXTURES

Using Dalton's law of partial pressure and the ideal gas law, the following equation can be derived for calculating the apparent molecular weight of a gas mixture:

(Eq. 2-7)

$$M_{mix} = \Sigma B_x M_x$$

where

M_{mix} = *apparent molecular weight of a gas mixture*
B_x = *proportion by volume of a gas component*
M_x = *molecular weight of a gas component*

In all other equations (except where specifically noted), the symbol M will be used to denote the molecular weight of a pure gas or a gas mixture.

GAS DENSITY

Gas density can be determined by rearranging Equation 2-6 and letting density $\varrho = m/V$:

(Eq.2-8)

$$\varrho = \frac{PM}{RT}$$

where

ϱ = *density*
P = *absolute pressure*
M = *molecular weight*
T = *absolute temperature*
R = *universal gas constant*

A method of determining density at T_s (stack temperature) and P_s (stack pressure) is to use the fact that there are 22.414 liters per gm-mole or 359 ft^3 per lb-mole at 32°F and 29.92 in. Hg, and to use the ideal gas law correction.

VISCOSITY

Origin and Definition of Viscosity

Viscosity is the result of two phenomena: (a) intermolecular cohesive forces, and (b) momentum transfer between flowing strata caused by molecular agitation perpendicular to the direction of motion. Between adjacent strata of a moving fluid, a shearing stress (Υ) that is directly proportional to the velocity gradient occurs (Figure 2-2).

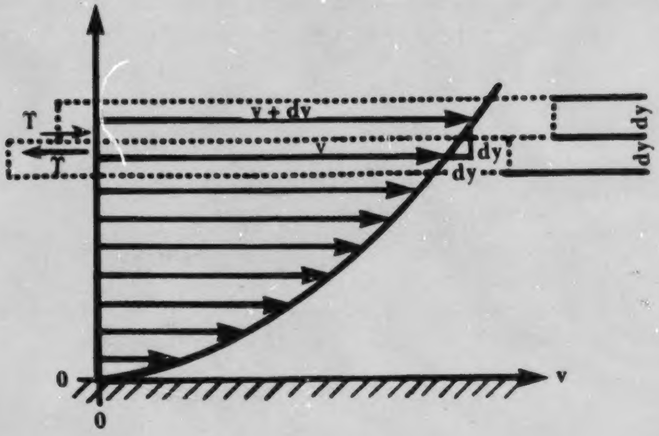


Figure 2-2. Shearing stress in a moving fluid.

This is expressed in the equation:

(Eq.2-9)

$$g_c \Upsilon = \mu \frac{dv}{dy}$$

where g_c = *dimensional constant*
Υ = *unit shearing stress between adjacent layers of fluid*
$\frac{dv}{dy}$ = *velocity gradient*
μ = *proportionality constant (viscosity)*

The proportionality constant, μ, is called the coefficient of viscosity, or merely, viscosity. It should be noted that the pressure does not appear in Equation 2-9 which indicates that the shear (Υ) and the viscosity (μ) are independent of pressure. (Viscosity actually increases very slightly with pressure but this variation is negligible in most engineering problems.)

Kinematic Viscosity

Kinematic viscosity is defined according to the following relationship:

(Eq.2-10)

$$\nu = \frac{\mu}{\varrho}$$

where ν = *kinematic viscosity*
μ = *viscosity of the gas*
ϱ = *density of the gas*

Note the absence of dimensions of force.

Liquid Viscosity

In a liquid, transfer of momentum between strata having a relative velocity is small compared to the cohesive forces between molecules. Hence, shear stress is predominantly the result of intermolecular cohesion. Because forces of cohesion decrease rapidly with an increase in temperature, the shear stress decreases with an increase in temperature. Equation 2-9 shows that shear stress is directly proportional to the viscosity. Therefore, liquid viscosity decreases when the temperature increases.

Gas Viscosity

In a gas, the molecules are too far apart for intermolecular cohesion to be effective. Thus, shear stress is predominantly the result of an exchange of momentum between flowing strata caused by molecular activity. Because molecular activity increases as temperature increases, the shear stress increases with a rise in the temperature. Therefore, gas viscosity increases as the temperature rises.

Determination of Viscosity of Gases

The viscosity of a gas for prevailing conditions may be found accurately from the following formula:

(Eq.2-11)

$$\frac{\mu}{\mu^\circ} = \left(\frac{T}{273.2}\right)^n$$

where

μ = *viscosity prevailing*
μ° = *viscosity at 0°C and prevailing pressure*
T = *absolute prevailing temperature (°K)*
n = *an empirical exponent* ($n = 0.768$ *for air*)

The viscosity of air and other gases at various temperatures and at a pressure of 1 atmosphere may be found in engineering tables.

SPECIFIC HEAT

The specific heat of a gas is the amount of heat required to change the temperature of a unit-mass of gas one temperature-degree. Units of specific heat are, therefore, (Btu/lb) (°F) or (calories/gm)(°C) depending upon the dimensional system used.

Heat may be added while the volume or pressure of the gas remains constant. Hence, there may be two values of specific heat: (a) the specific heat at constant volume (C_v), and (b) the specific heat at constant pressure (C_p).

Because the heat energy added at constant pressure is used in raising the temperature and doing work against the pressure as expansion takes place, C_p is greater than C_v.

Determination of Specific Heat for a Gas Mixture

The specific heat for a mixture of gases may be calculated from:

(Eq.2-12) $$C_p(mix) = \Sigma B_x C_{p(x)}$$

(Eq.2-13) $$C_V(mix) = \Sigma B_x C_{V(x)}$$

where $C_p(mix)$ = *specific heat at constant pressure for gas mixture*
$C_V(mix)$ = *specific heat at constant volume for the gas mixture*
B_x = *proportion by volume of a gas component*
$C_{p(x)}$ = *specific heat at constant pressure for a gas component*
$C_{V(x)}$ = *specific heat at constant volume for a gas component*

For ordinary temperature (for example, about 80°F as experienced at the metering device in atmospheric or source sampling work) the specific heats may be assumed to be constant.

REYNOLDS NUMBER

Definition

A typical inertial force per unit volume of fluid is $\varrho v/gcL$; a typical viscous force per unit volume of fluid is $\mu v/gcL^2$. The first expression divided by the second provides the dimensionless ratio known as **Reynolds Number:**

(Eq.2-14) $$N_{Re} = \frac{Lv\varrho}{\mu}$$

where ϱ = *density of the fluid (mass/volume)*
v = *velocity of the fluid*
g_c = *dimensional constant*
L = *a linear dimension*
μ = *viscosity of the fluid*
N_{Re} = *Reynolds Number*

The larger the Reynolds Number, the smaller is the effect of viscous forces; the smaller the Reynolds Number, the greater the effect of the viscous forces.

The linear dimension, *L*, is a length characteristic of the flow system. It is equal to four times the mean hydraulic radius, which is the cross-sectional area divided by the wetted perimeter. Thus for a circular pipe, *L* = diameter of the pipe; for a particle settling in a fluid medium, *L* = diameter of the particle; for a rectangular duct, *L* = twice the length times the width divided by the sum; and for an anulus such as a rotameter system, *L* = outer diameter minus the inner diameter.

Laminar and Turbulent Flow

In **laminar** flow, the fluid is constrained to motion in layers (or laminae) by the action of viscosity. The layers of fluid move in parallel paths that remain distinct from one another; any agitation is of a molecular nature only. Laminar flow occurs when Reynolds Number for circular pipes is less than 2000 and less than 0.1 for particles settling in a fluid medium.

In **turbulent** flow, the fluid is not restricted to parallel paths but moves forward in a haphazard manner. Fully turbulent flow occurs when Reynolds' Number is greater than 2500 for circular pipes and greater than 1000 for settling particles.

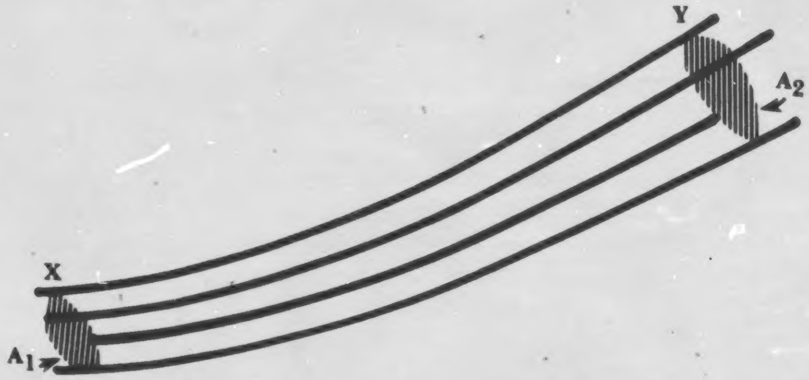


Figure 2-3. A tube of flow used in proving the equation of continuity.

THE EQUATION OF CONTINUITY[*]

In Figure 2-3 we have drawn a thin tube of flow. The velocity of the fluid inside, although parallel to the tube at any point, may have different magnitudes at different points. Let the speed be v_1 for fluid particles at X and v_2 for fluid particles at Y. Let A_1 and A_2 be the cross-sectional areas of the tubes perpendicular to the streamlines at the points X and Y, respectively. In the time interval Δt, a fluid element travels approximately the distance $v\Delta t$. Then the mass of fluid Δm crossing A_1 in the time interval is approximately

$$\Delta m_1 = \varrho_1 A_1 v_1 \Delta t$$

or the mass flux $\Delta m_1 / \Delta t$ is approximately

$$\frac{\Delta m_1}{\Delta t} = \varrho_1 A_1 v_1$$

---

[*] Adapted from D. Halliday and R. Resnick, *Physics for Students of Science and Engineering*, Combined Edition, New York, John Wiley and Sons, Inc., 1965, pp. 374-378. Used by permission of the publisher.

We must make Δt small enough so that in this time interval neither v nor A varies appreciably over the distance the fluid travels. In the limit as $\Delta t \rightarrow 0$, we obtain the precise result

$$\frac{dm_1}{dt} = \varrho_1 A_1 v_1 \text{ at } X.$$

Now at Y the mass flux is correspondingly

$$\frac{dm_2}{dt} = \varrho_2 A_2 v_2 \text{at } Y.$$

where ϱ_1 and ϱ_2 are the fluid densities at X and Y respectively. Since no fluid can leave through the walls of the tube and there are no "sources" or "sinks" wherein fluid can be created or destroyed in the tube, the mass crossing each section of the tube per unit time must be the same. Hence, $dm_1/dt = dm_2/dt$. Then

(Eq.2-15)

$$\varrho_1 A_1 v_1 = \varrho_2 A_2 v_2,$$

$$\varrho A v = constant$$

This result is called the **equation of continuity of mass flow.** It expresses the law of conservation of mass in fluid dynamics.

If the fluid is incompressible, then $\varrho_1 = \varrho_2$ and the equation takes on the simpler form:

(Eq.2-16)

$$Av = constant$$

$$A_1 v_1 = A_2 v_2$$

BERNOULLI'S EQUATION

A fundamental equation of fluid dynamics is Bernoulli's Equation. It is essentially a statement of the work-energy theorem for fluid flow.

Consider the nonviscous, steady, incompressible flow of a fluid through the pipeline or tube of flow in Figure 2-4. The portion of pipe shown in the figure has a uniform cross section A_1 at the left.

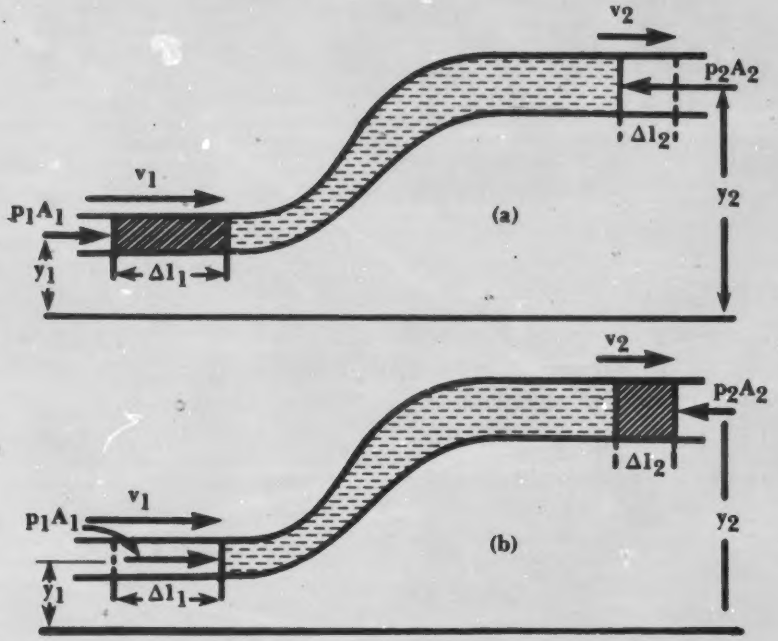


Figure 2-4. A portion of fluid (cross-shading and horizontal shading) moves through a section of pipeline from position (a) to position (b).

It is horizontal at elevation y_1 above some reference level. It gradually widens and rises and then has a uniform cross section A_2 (at the right of the figure). It is horizontal at elevation y_2. Let us concentrate our attention on the portion of fluid represented by both cross-shading and horizontal shading and call this fluid the "system." Consider then the motion of the system from the position shown in (a) to that in (b).

At all points in the narrow part of the pipe, the pressure is p_1 and the speed v_1. At all points in the wide part the pressure is p_2 and the speed v_2. The left portion of the system (cross-shading, Figure 2-4a) advances a distance Δl_1, parallel to an external force p_1A_1 supplied by the fluid to its left, so that the work done on the system is $p_1A_1\Delta l_1$. The right portion of the system (cross-shading, Figure 2-4b) advances a distance Δl_2 against an oppositely directed force p_2A_2 supplied by the fluid beyond, so that the work done by the system is $p_2A_2\Delta l_2$. Hence, to move the system from position (a) to position (b), a net amount of work must be done on the system by the pressures applied to it equal to $p_1A_1\Delta l_1 - p_2A_2\Delta l_2$.

$A_1\Delta l_1$ and $A_2\Delta l_2$ are the volumes of the two cross-shaded regions. These volumes are equal because the fluid is incompressible. In fact, if we let m be the mass of either cross-shaded region and take fluid density to be r then

(Eq.2-17) $$A_1\Delta l_1 = A_2\Delta l_2 = \frac{m}{\varrho}$$

and

(Eq.2-18) $$(p_1 - p_2)\frac{m}{\varrho} = \textit{net work done on system.}$$

If our pipe has a continuously variable cross section, this analysis can be made exact by considering the process in the limit as Δl_1, Δl_2, and Δt shrink to zero at the points 1 and 2. The result is the same as before.

If the flow is nonviscous, the net work done on the system by pressure must equal the net gain in mechanical energy. The horizontal shaded portion of the fluid does not change at all in either kinetic or potential energy during the flow from (a) to (b). Only the cross-shaded portions contribute to changes in mechanical energy. In fact, $\frac{1}{2}mv_2^2 - \frac{1}{2}mv_1^2$ = net change of kinetic energy, and $mgy_2 - mgy_1$ = net change in gravitational potential energy, where m is the mass in either cross-shaded region, and g is the gravitational constant. Hence,

(Eq.2-19) $$(p_1 - p_2)\frac{m}{\varrho} = (\tfrac{1}{2}mv_2^2 - \tfrac{1}{2}mv_1^2) + (mgy_2 - mgy_1)$$

or on rearranging terms,

(Eq.2-20) $$p_1 + \tfrac{1}{2}\varrho v_1^2 + \varrho g y_1 = p_2 + \tfrac{1}{2}\varrho v_2^2 + \varrho g y_2.$$

Since the subscripts 1 and 2 refer to any two locations along the pipeline, we can drop the subscripts and write

(Eq.2-21) $$p + \tfrac{1}{2}\varrho v^2 + \varrho g y = \textit{constant.}$$

Either Equation 2-20 or Equation 2-21 is called **Bernoulli's Equation** for steady, nonviscous, incompressible flow. It was first presented by Daniel Bernoulli (1700-1782) in his *Hydrodynamica* in 1738.

Bernoulli's Equation is strictly applicable only to steady flow. The quantities involved must be evaluated along the same streamline; hence, the constant Equation 2-21 is not the same for all streamlines. In our figure the streamline used is along the lower boundary of the tube of flow or pipeline.

In the special case of fluid statics, Bernoulli's Equation still holds. If the fluid is at rest then $v_1 = 0 = v_2$ and Equation 2-20 becomes

(Eq.2-22) $$P_1 + \varrho g y_1 = P_2 + \varrho g y_2$$
$$P_2 - P_1 = -\varrho g(y_2 - y_1)$$

The pressure that would be present even if there were no flow is denoted as the static pressure; the term $\frac{1}{2}\varrho v^2$ is called the dynamic pressure.

Chapter 3

The EPA Method 5 Sampling Train

Specialized equipment is required for performing the experimental procedures outlined in Federal Reference Methods 5 and 8. This equipment may be either constructed by the source tester or purchased from a commercial vendor. It is more common today to find stack test consulting companies and agency test teams using the commerical apparatus. A list of vendors currently marketing such equipment may be found in the appendix. Construction details for the Method 5 sampling train may be found in the EPA publication APTD 0581 available from the National Technical Information Service(NTIS).

The purpose of this chapter is to provide the reader with some insight into the design and construction of source sampling apparatus. A proper evaluation of sampling equipment must consider both the equipment's ability to conform to Federal or State construction guidelines and its actual utility in the field. This discussion should assist the reader in purchasing the source sampling train or in the construction of such a system.

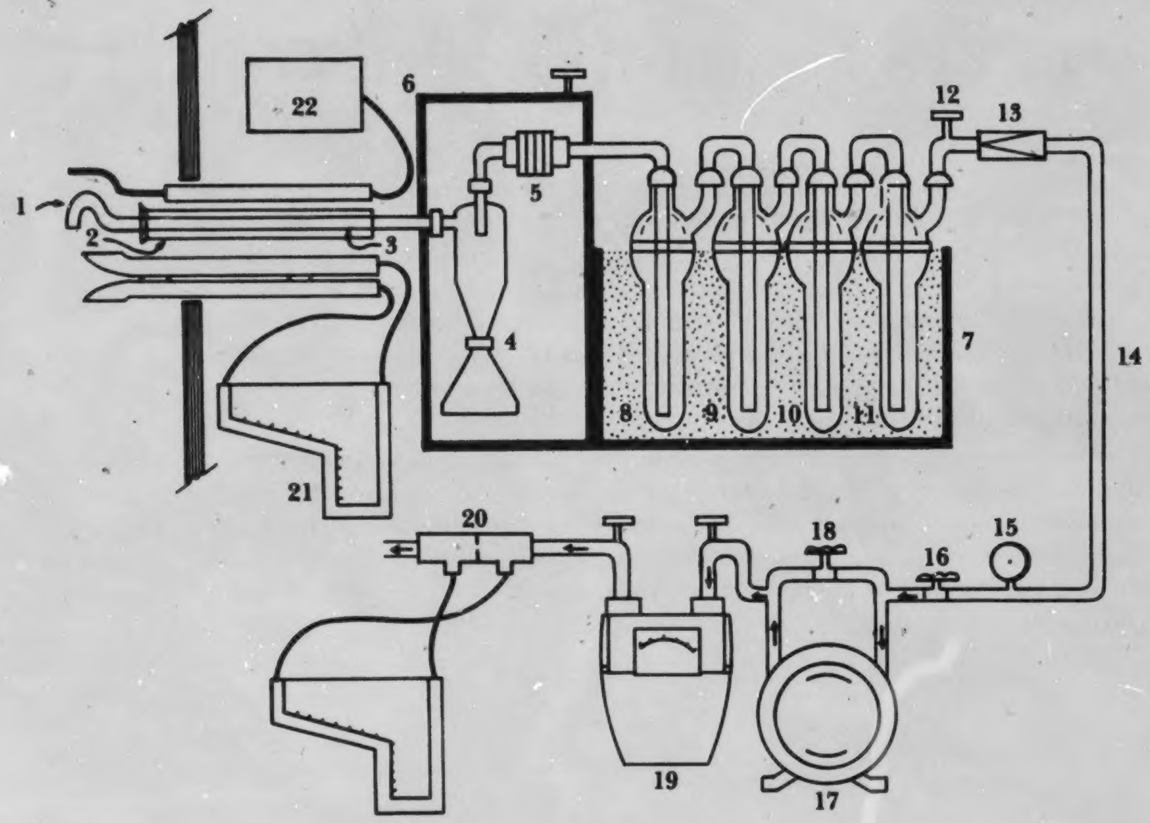


Figure 3-1. EPA Method 5 particulate sampling train

1. Sampling nozzle
2. Sampling probe sheath
3. Heated sample probe liner
4. Cyclone assembly (proposed regulations do not require this cyclone)
5. Out of stack filter assembly
6. Heated filter compartment maintained 120°C ± 14°C (248°F ± 25°F)
   (or temperature specified in 40CFR subpart)
7. Impinger case
8. First impinger filled with H_2O (100 ml)
9. Greenburg-Smith (or modified Greenburg-Smith) impinger filled with H_2O (100 ml)
10. Third impinger – dry
11. Fourth impinger – filled with H_2O absorption media (200-300 gm)
12. Impinger exit gas thermometer
13. Check valve to prevent back pressure
14. Umbilical cord – vacuum line
15. Pressure gage
16. Coarse adjustment valve
17. Leak free pump
18. By-pass valve
19. Dry gas meter with inlet and outlet dry gas meter thermometer
20. Orifice meter with manometer
21. Type S pitot tube with manometer
22. Stack temperature sensor

THE SOURCE SAMPLING NOZZLE

The source sampling nozzle must have a sharp outside edge (taper angle ≤30°) and a button-hook or elbow design. This profile creates the least amount of disturbance to the gas streamlines. Figure 3-2 illustrates the preferred sampling nozzle shape.

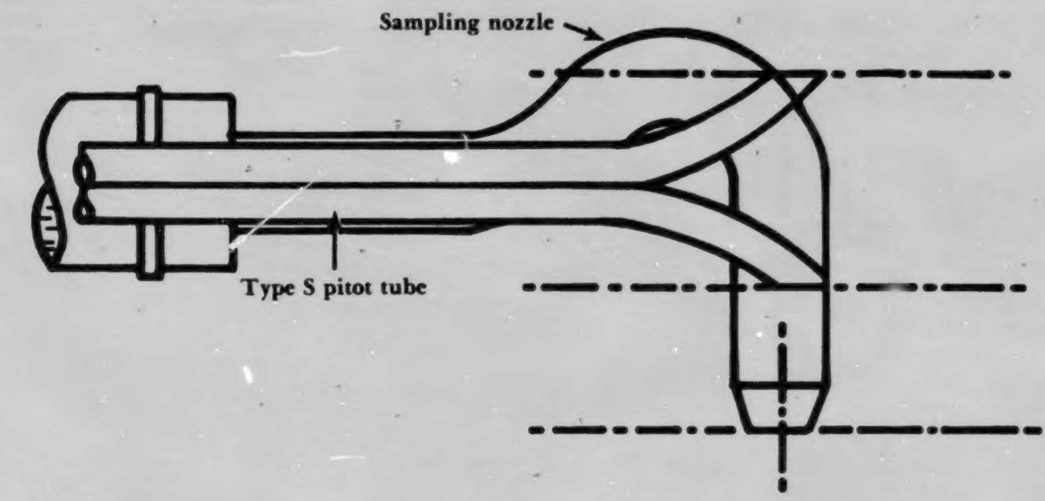


Figure 3-2. Preferred sampling nozzle shape (assembled with Type S pitot tube).

The nozzle interior diameter must be accurately calibrated following the procedure given in the calibration section of this manual. Manufacturer calibration is only a nominal approximation, and calibration of nozzle interior diameter should be checked with a micrometer before the nozzle is placed on the sampling probe at the test site. The sampling nozzle interior diameter must be round and uniform throughout its entire length. If the tip is out-of-round it must be rounded, ground to a sharp edge, and recalibrated. If the nozzle has obvious flat places in its body it should be replaced with a nozzle of uniform diameter. The nozzle must properly align with pitot tube sensing orifices so that one line can be drawn through the central axis of the interior nozzle diameter opening and of the pitot orifice. The nozzle must not be too short or too long; if the central axis of the pitot tube is not on the same line as the nozzle diameter, it must be parallel and not more than ¼" off-center (Figure 3-3).

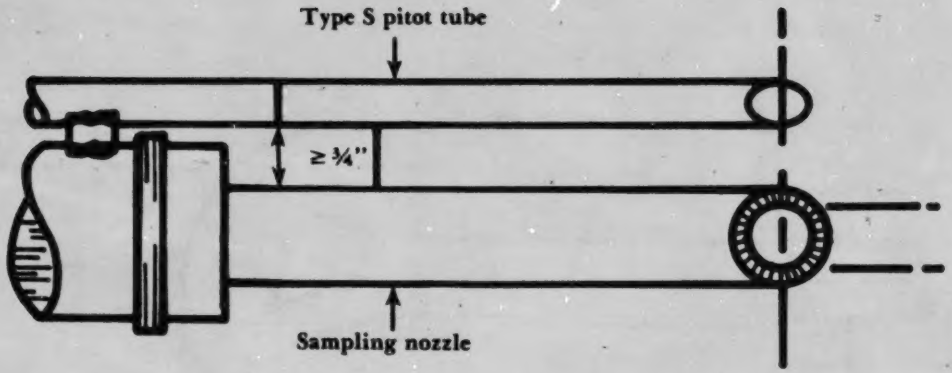


Figure 3-3. Pitot tube-nozzle separation and alignment.

A nozzle not meeting all these criteria does not comply with *Federal Register* specifications and can create sampling errors. Sampling nozzles constructed of stainless steel or quartz glass (for special applications) are required.

THE PITOT TUBE

The Stausscheibe or Type S pitot tube is most frequently used in conjunction with the Method 5 or Method 8 sampling train. The Type S pitot tube has several advantages that makes it attractive for source sampling applications:

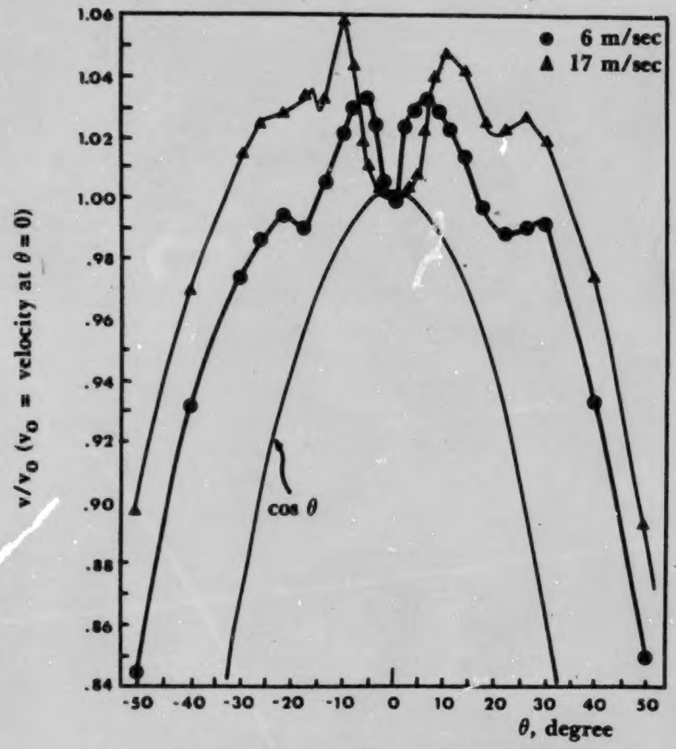
- It is compact. It is easy to insert into a 3" sampling port.
- It retains calibration in abusive environments.
- It has large sensing orifices. This minimizes the chance of plugging in heavy particulate concentrations.
- It indicates a higher Δp reading than a standard pitot tube which is beneficial in low gas velocity situations.

The Stausscheibe pitot is not a designated standard. It must be calibrated against a standard pitot static tube with a known calibration factor. Manufacturer calibration coefficents are not sufficient. The lack of standard construction details and the high sensitivity to gas turbulence and orientation in the gas stream require that the Type S tube be calibrated in the configuration intended *at the sampling site*.

The construction of the Type S tube must be checked before calibration. Calipers are used to check that the tubes are in line at the sensing orifice. The dimensions taken with the calipers must form a rectangle with parallel sides. If these dimensions show the A and B legs to be improperly aligned, the Type S tube must be corrected. Small misalignment of tube axis (A or B) can cause sufficient gas turbulence to effect pitot tube calibration. The tube should be made of stainless steel or quartz (for high temperature applications).

SAMPLING PROBE—PITOT TUBE ASSEMBLY

The pitot tube should be firmly attached to the sampling probe and properly oriented. The probe-pitot assembly must be arranged in such a way that the pitot tube body will be oriented perpendicular to the stack wall when sampling. The sensing orifices will then be perpendicular to the flow of gas parallel to the stack. This orientation is necessary for precise, accurate gas velocity readings. A Type S pitot tube incorrectly oriented to the stack gas can cause significant errors in gas velocity readings (Figure 3-4).



Adapted from E. F. Brooks and R. L. Williams, *Flow and Gas Sampling Manual*, EPA-600/2-76-203, July 1976, p. 59.

Figure 3-4. Type S pitot probe orientation sensitivity data.

The pitot must be firmly attached to the probe so it will not slip accidently into misalignment.

The stainless steel probe sheath should be of 316 stainless steel or equivalent. The sheath should be at least 3 inches from the pitot tube sensing orifices, and any nozzle must be at least ¾ inches from this orifice when attached to the probe (Figure 3-3). A small hole should be drilled into the stainless sheath to equalize any pressure differential that might allow dilution air to be pulled into the sampling system.

The sheath is designed to protect the heated liner. Tolerances in the sheath should be such that probe liner heating element short circuits are not a problem during normal operation. The liner should be borosilicate glass for sampling stack gases below 700°F. Quartz glass may be used in the sheath for temperatures up to 1400°F. Stainless steel liners are subject to corrosion by hot, acidic stack gases. They should be a last choice except for very difficult sampling applications or for sampling probes over 11 feet long. A liner heated by an easily-removed, reusable heating element can be replaced at minimum cost. The probe heater should be calibrated so that the outlet gas temperature at the filter is known.

The liner should be cleaned with a probe brush. A brush of non-reactive nylon and stainless steel with strongly attached bristles is appropriate (bristles must not fall into the sample). It should be attached to a stainless steel or teflon tube that can be telescoped with additional sections.

THE SAMPLING CASE

A lightweight, easily adaptable sampling case is an asset during sampling experiments. A well-designed sample case can be made from lightweight material and yet withstand source sampling abuses. The case should incorporate solid construction and well-insulated electrical connections, and it should be usable in either vertical or horizontal positions. The filter compartment must have a calibrated thermostat. A positive locking system to prevent probe-pitot rotational or tilt misalignment in the stack is also necessary. The probe sheath should be able to be inserted in the sample case so that there is no accidental glass breakage. An example of the described system is illustrated in Figure 3-5.

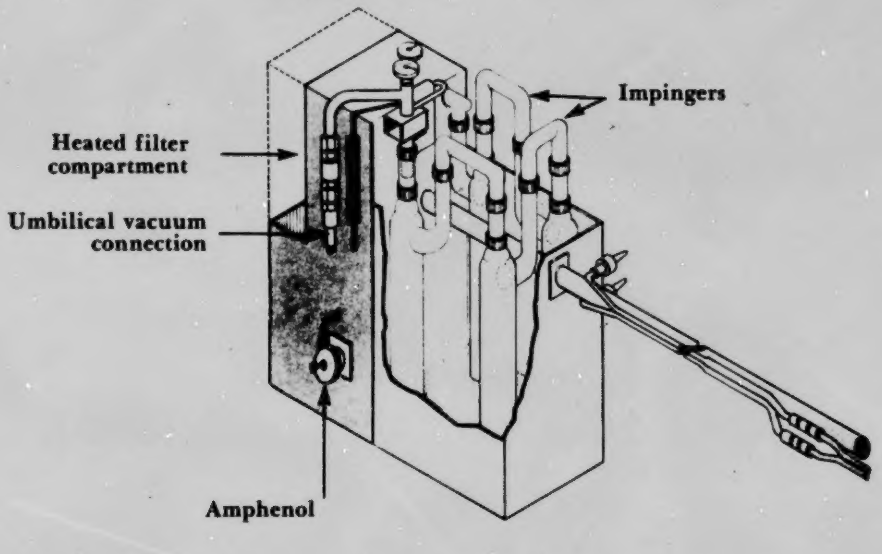


Figure 3-5. Sampling case.

A single-point swivel suspension system for the sample case is advantageous in tight work area situations.

TRAVERSE SUPPORT SYSTEM

A monorail support is versatile and lightweight. An inexpensive monorail support system with a lubricated roller hook can be easily assembled. It may be used at a variety of sampling sites for horizontal or vertical duct traverses. An entire system can be cheaply assembled with some lengths of chain, double-ended snaps, angle iron, and eye bolts. A simple platform constructed of plywood and 2 × 4's will be sufficient in many situations where a monorail is not practical.

SAMPLE CASE GLASSWARE

There are several types of impinger-filter sets available for source sampling trains. Sample case impingers and filter holders are generally made of Pyrex glass, but special situations could call for the stainless steel or Lexan plastic equipment. Glass has obvious advantages and should be used unless unusual situations arise. The glassware is available in standard ball joint fittings that are sealed with vacuum grease and clamped together or in a newer screw-joint sealed with a compressible teflon-rubber ring. The newer screw-joint fittings increase breakage; however, they are easier to clean, and grease contamination of the sample is never a problem.

THE UMBILICAL CORD

The vacuum sampling line, pitot tube lines, and electrical wiring are wrapped into an "umbilical cord" extending from the meter console to the sample case. These lines are encased in tape or shrink tubing to protect them and eliminate clutter at the sample site. The vacuum line should be of high-vacuum rubber tubing. The pitot lines are best constructed of heavy-ply tygon tubing. These materials make the umbilical cord heavier, but they are not easily melted, burned, or cut. Sample cords made of polymeric materials can be easily damaged without notice and then begin to leak. The electrical wires should have thick insulation to prevent fraying in heavy use. They should be color coded and attached to an Amphenol connection for easy hookup to the sample case.

THE METER CONSOLE

The meter console is the center of the sampling system. A packaged pump-dry gas meter-orifice system is easiest to handle, but there are many suitable variations in use. The system must have a leak-free pump to draw an isokinetic sample. A fiber vane, oil lubricated pump, or diaphragm pump capable of creating an absolute pressure of $\leq$ 3 inches of Hg ($\leq$ 30 inches Hg gage) is recommended. A fiber vane pump is more desirable than a diaphragm pump, because it does not give "pulses" of gas that can create errors in the operation of the dry gas meter.

The pump should force gas into the dry gas meter *inlet*, not pull it through the meter *outlet*. The dry gas meter sliding vane seals are adversely affected when under vacuum, so a vacuum gage should be in the system to measure pressure drop across the sampling train.

The dry gas meter must be accurate. The manufacturer supplies a nominal calibration curve with the meter which should be rechecked before using the meter. A dry gas meter correction factor developed by calibration against a spirometer or wet test meter is important for volume readings from the meter. The meter dial face should measure 0.1 cubic feet of gas per revolution. This gives the most precise volume reading.

The differential pressure gage recommended in the *Federal Register* is an oil manometer. The manometer must be capable of measuring the velocity pressure to within 1.3 mm (0.05 in.) water column. The oil manometer is a secondary standard and is very accurate. A Magnehelic gage may be used if it is calibrated before a test series, then checked after each test series against an oil manometer. The Magnehelic gage must be calibrated and checked at three Δp readings representing the range encountered at the source. The Magnehelic gage and oil manometer must agree within 5 percent for the Magnehelic gage to be considered in proper calibration.

The meter console or equivalent apparatus must be capable of monitoring and maintaining all the equipment temperatures in addition to measuring stack gas temperature. Bimetallic thermometers in the sample case for impinger gas exit temperature are acceptable if they are precise to within 1 °C (2 °F). The temperature at the dry gas meter and at the filter compartment must be measured with a precision of 3 °C (5.4 °F). Some method of regulating the calibrated probe liner heater and filter heater must be incorporated into the temperature control system. The stack gas temperature meter must measure gas temperature to 1.5 percent of the minimum absolute stack gas temperature. A meter console using thermocouples for these operations must have the thermocouples calibrated regularly and checked before each use.

THE NOMOGRAPH

A number of nomographs are available commercially. The nomograph makes several assumptions in its calculations, but these assumptions may not always hold true for all sampling situations. The alignment and accuracy of nomograph functions should be checked using the procedures given in this manual. A pocket calculator can solve the isokinetic equation accurately and inexpensively.

ALTERNATIVE METHODS AND EQUIPMENT

There are a number of alternative methods for isokinetic sampling of stack gas particulates. The Japanese and West German methods have received attention in many countries, and the American Society of Mechanical Engineers has also developed isokinetic sampling methods. These alternative methods may be highly attractive for some situations. This manual and the *Federal Register* reference methods recognize only the methods described herein. The use of methods other than those described in the *Federal Register* requires special approval from the regional administration assessing the effects that alternative methods may have on sampling results.

Chapter 4

Calibration Procedures

Source sampling equipment must be properly calibrated before it is used in the field. Systematic errors will result throughout the testing procedure as a result of uncalibrated or improperly calibrated equipment. Without calibration, the stack tester cannot sample isokinetically in any of his source tests, and he cannot correct the mass emission rate data if the equipment is calibrated *after* the test. It is therefore crucial that the apparatus used for stack testing be carefully checked. A manufacturer's calibration value or guarantee should not be trusted. It is not uncommon to find miscalibrated apparatus supplied by a vendor, and over extended use instrument calibration values can change.

A careful experimentalist always double checks his apparatus. Weeks of work may otherwise be questioned or may need to be redone. This section gives calibration procedures and design specifications for equipment commonly used in the source test. The procedures should be followed after receipt of new equipment and should be repeated after periods of extended use.

CALIBRATION OF THE SOURCE SAMPLING METER CONSOLE

The gas meter and orifice meter of a sampling console may be calibrated during one procedure. The calibration described in this section may be performed using a standardized dry gas test meter or wet test meter. The sampling console must be thoroughly leak tested before calibration.

Calibration Equipment

1. Calibrated test meter
   a. Wet test meter (correction factor should be 1.0 for wet test meter)
   b. Standardized dry gas test meter
2. Sampling meter console
   a. Dry gas meter
   b. Orifice meter
3. Stopwatch
4. Leak-free pump (fiber vane, preferably)
5. Vacuum tubing
6. Swagelock connections
7. Leak test liquid

Meter Console Leak Test

The meter console pump, dry gas meter, and orifice meter must be leak tested before calibration. This leak test can be accomplished by individually testing each piece of equipment or by leak testing the entire assembly. The *Federal Register* suggests a procedure for leak testing the assembled pump, dry gas meter, and orifice configuration (Figure 4-1). The following procedure, however, does **not** apply to diaphragm pumps.

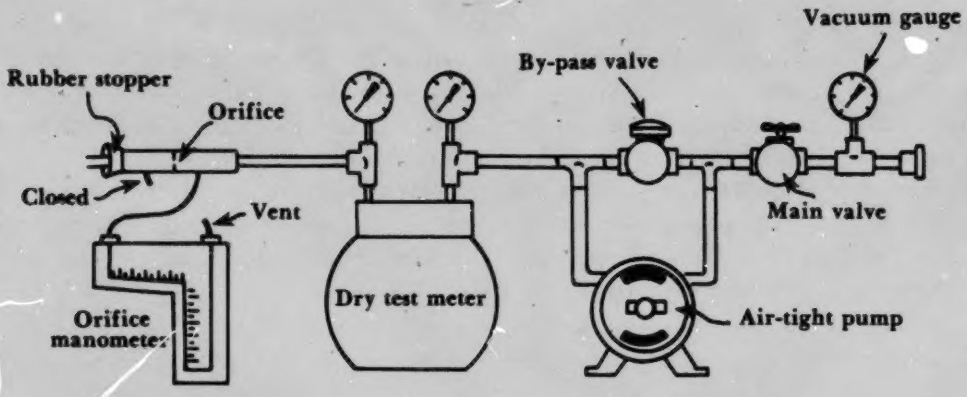


Figure 4-1. Leak check for the Method 5 meter console.

1. Plug the orifice meter outlet with a one-hole rubber stopper that has a rigid tube through the hole.
2. Attach a length of rubber tubing (an inline toggle valve in the tubing would be helpful).
3. Disconnect the static pressure side tubing of the orifice manometer and close off the tube. Leave the static tap of the manometer open to a vent position.
4. Completely open the bypass valve by turning it counter-clockwise to a lock position; close the coarse adjustment valve.
5. Blow into the rubber tubing, plugging the orifice until the manometer shows a pressure differential greater than 6 in. H_2O.
6. Seal the tubing (close toggle valve). The manometer reading should remain stable at least 1 minute.
7. If a leak occurs, completely disconnect the orifice manometer and seal the orifice meter. Pressurize the system using a small pump and find the leak with leak test solution.

Meter consoles with diaphragm pumps can be leak checked by pulling an air sample through a wet test meter-pump-dry gas meter setup. The leak rate should not exceed 0.0057 m^3/min. (0.02 cfm).

10

Meter Console Calibration

The meter console calibration is accomplished with the equipment assembled as shown in Figure 4-2.

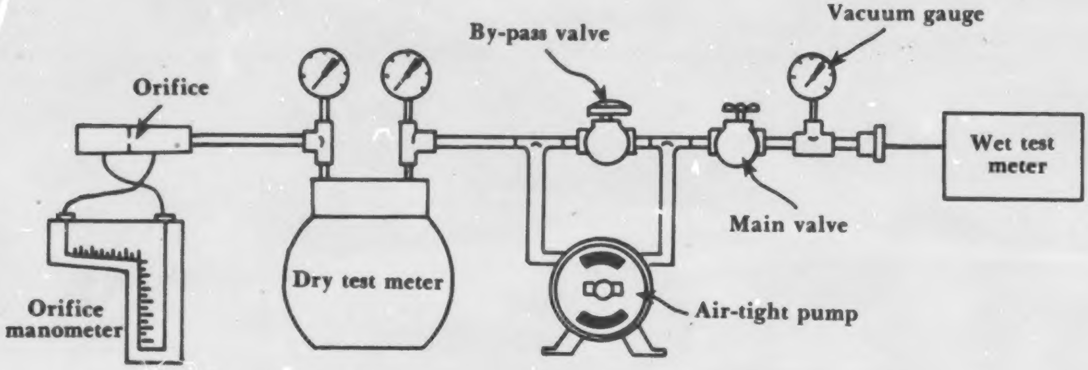


Figure 4-2. Meter console calibration assembly.

The wet test meter should have a correction factor of 1. (A standardized dry gas meter may also be used to calibrate the meter console.) The calibration of the meter console dry gas meter and orifice meter is accomplished by passing a known volume of dry air through the test meter at a number of different pressure differentials on the orifice manometer.

In the calibration procedure:

1. Establish a pressure differential (ΔH) across the orifice meter with the pump and the coarse and fine adjustment valves.
2. Accurately record the dial readings for the wet test meter and dry gas meter while simultaneously starting a stopwatch.
3. Draw a predetermined volume of air (e.g. 5 cubic feet) through the test meter. Record all temperatures during the calibration run.
4. Stop the pump when the predetermined volume has been reached on the wet test meter; simultaneously record the total elapsed time.
5. Make all calculations on the calibration form for this procedure (Figure 4-3).

Note: The standard temperature given by APTD-0576 (70°F) has since been changed to 68°F, although the publication itself does not reflect this change.

METER CONSOLE CALIBRATION

Name________________________ Date ________________________

Console no. ______ Dry gas meter no. ______ Dry gas meter correction factor ______

Wet test meter no. ____________________ Correction factor ____________________

Barometric pressure, P_b __________ in. Hg previous calibration and date __________

Orifice manometer setting, ΔH, in. H_20	Gas volume wet test meter V_w, ft^3	Gas volume dry gas meter V_d, ft^3	Temperature					Time θ min	γ	$\Delta H_@$
			Wet	Dry gas meter						
			Meter t_w, °F	Inlet t_{di}, °F	Outlet t_{do}, °F	Average t_d, °F				
0.5	5									
1.0	5									
2.0	10									
4.0	10									
6.0	10									
8.0	10									
							Average			

Calculations

ΔH	$\frac{\Delta H}{13.6}$	γ $\frac{V_w P_b (t_d + 460)}{V_d \left(P_b + \frac{\Delta H}{13.6}\right)(t_w + 460)}$	$\Delta H_@$ $\frac{0.0317\ \Delta H}{P_b (t_d + 460)} \left[\frac{(t_w + 460)\theta}{V_w}\right]^2$
0.5	0.0368		
1.0	0.0737		
2.0	0.147		
4.0	0.294		
6.0	0.431		
8.0	0.588		

γ = Ratio of accuracy of wet test meter to dry test meter. Tolerance = ± 0.02.

$\Delta H_@$ = Orifice pressure differential that gives 0.75 cfm of air at 68°F and 29.92 inches of mercury, in. H_20. Tolerance = ± 0.15 inches.

Orifice $\Delta H_@$ should fall between 1.59 - 2.09 inches, or modification may be necessary for some sampling situations.

Figure 4-3. Form for meter console calibration

CALIBRATION OF TEMPERATURE MEASUREMENT DEVICES

The Method 5 source sampling system requires gas temperature measurements at several locations. The temperature measurements are important for correcting stack gas parameters to standard condition. Accurate measurement within the tolerance given in the *Code of Federal Regulations* is essential. Procedures are given here for calibrating general types of temperature sensor devices. Manufacturer recommendations for special temperature sensors should be carefully followed.

Temperature Reference

A commercially available mercury thermometer capable of ± 1° sensitivity is sufficient for calibration purposes. The thermometer should be immersible in ice water, boiling water, hot mineral oil, or a tube furnace. The thermometer scale should cover the range of anticipated source temperatures.

Bimetallic Thermometer Calibration

Dial or bimetallic thermometers are used for temperature measurement in several train locations. Adjustable dial thermometers are calibrated by immersion in a water bath along with the mercury thermometer. Temperature readings should be taken at several points on the dial thermometer scale, and its reading should be set to correspond with the corrected mercury thermometer measurement (adjusted for elevation above sea level). Non-adjustable dial thermometers must agree with the corrected mercury thermometer temperature within 3°C (5.4°F), if used at the filter heater compartment, and within 1°C (2°F) when used at other locations in the sampling train.

It is unlikely that a dial or a bimetallic thermometer would be used to monitor in-stack gas temperature at most sources. If either is used for stack measurements, it must be calibrated to read stack temperature to within 1.5 percent of the minimum absolute stack gas temperature.

Thermocouples

An electromotive force is produced when two connected, dissimilar metal wires are subjected to temperature variations. The electromotive force (EMF) is fixed for a given combination of metals and is proportional to the temperature of the metal wires at the measurement junction. A cold or reference junction is maintained at the metering device. Potentiometers or millivoltmeters are commonly used to measure EMF. The voltage signals are, today, usually converted to read directly in degrees on either an analog or digital meter.

Thermocouple wires are necessarily thin to speed response time and increase EMF sensitivity. They must be thoroughly inspected on a routine basis. Any frayed or damaged wire should be replaced or repaired. Insulation must be complete, or wires could short against metal surfaces. The thermocouple junction should be either welded or silver-soldered.

The thermocouple should be calibrated with the millivoltmeter that will be used in the field. The voltmeter should first be zeroed and calibrated according to the manufacturer's instructions. The following procedure should then be followed:

1. Connect the meter to the thermocouple.
2. Check the thermocouple reading with that of a mercury thermometer at several readings:
    a. boiling water
    b. ice point
    c. ambient air

If the temperature at the stack is greater than that of boiling water, several calibration points across the anticipated temperature range should be made. This may be done by using hot mineral oil, tube furnace, or another apparatus that allows thermocouple and mercury thermometer comparison. The thermocouple should be thoroughly cleaned after it is calibrated in a material such as mineral oil. Do not immerse ceramic-covered thermocouples in a liquid calibration medium: they absorb the liquid, and that can affect reading during calibration or in field use.

3. Record the data (Figure 4-4).
4. Make the proper adjustments (if possible) on the voltmeter to read the proper temperatures.
5. If the meter cannot be adjusted to reflect the proper temperatures, construct a calibration curve and include it in your field notebook.

TEMPERATURE CALIBRATION

Name ______________________ Date ______________________

Barometric Pressure ______________________ Land Elevation ______________________

ICE BATH

Hg in Glass Thermometer Temperature				Corrected Hg in Glass Temperature				Temperature Device ______ Identification No. ______ Temperature			
°C	°K	°F	°R	°C	°K	°F	°R	° C	° K	° F	° R

BOILING WATER BATH

Hg in Glass Temperature				Corrected Temperature				Device ______ No. ______			
°C	°K	°F	°R	°C	°K	°F	°R	° C	° K	° F	° R

MINERAL OIL BATH

Point	Hg in Glass Temperature				Corrected Temperature				Device ______ No. ______			
	°C	°K	°F	°R	°C	°K	°F	°R	° C	° K	° F	° R
1												
2												
3												
4												

Figure 4-4. Form for temperature calibration.

CALIBRATION OF THE TYPE S (STAUSSCHEIBE) PITOT TUBE

The Type S pitot tube has several advantages as a gas velocity pressure measurement instrument in particulate-laden gas streams. The Type S tube is compact. Separately or attached to a sampling probe, the tube fits easily into a 3-inch diameter sampling port. The Type S pitot tube maintains calibration in abusive environments, and its large sensing orifices minimize plugging by particulates. The Type S pitot tube also gives a high manometer reading for a given gas velocity pressure, which is helpful in stacks with low gas velocity. These features make the Type S pitot tube the most frequently used source sampling pitot tube.

The Type S pitot tube construction details should be carefully checked before calibration. The tube should be made of stainless steel or quartz (for high temperature gas streams) with a tubing diameter (D_t) between 0.48 and 0.95 cm (3/16"-3/8"). The distance from the base of each pitot tube leg to the plane of the orifice opening (P_A, P_B) should be equal (Figure 4-5).

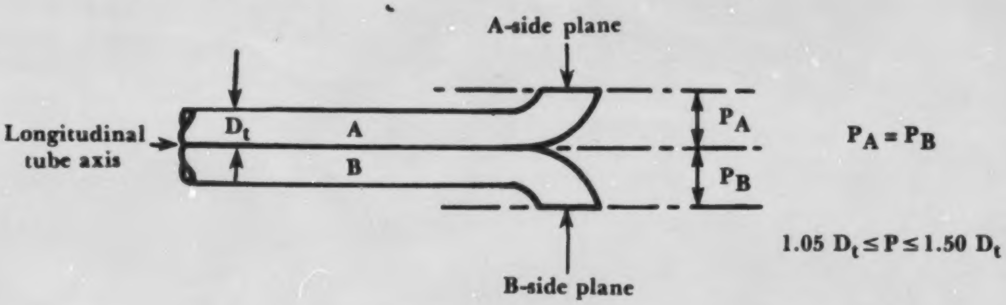


Figure 4-5. Type S pitot tube leg alignment.

P_A and P_B should be between 1.05 and 1.50 times the tubing diameter. Pitot tube orifice face openings should be properly aligned as shown in Figure 4-6. Misalignment of these openings can affect the pitot tube calibration coefficient and should be corrected before calibration.

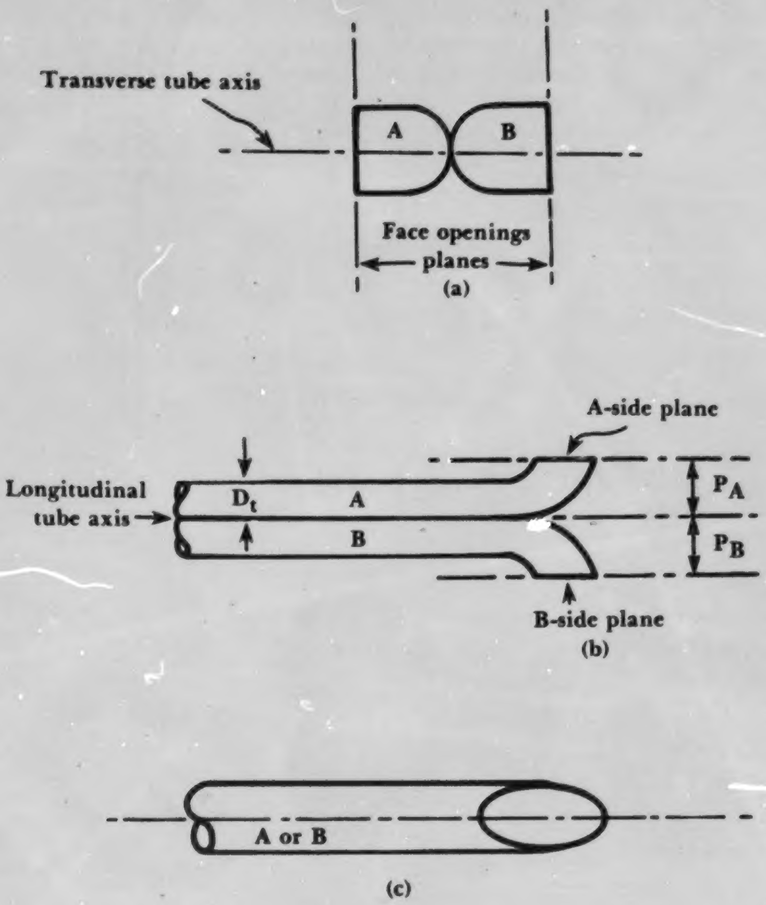

Transverse tube axis
A
B
Face openings planes
(a)
A-side plane
Longitudinal tube axis
D_t
A
B
P_A
P_B
B-side plane
(b)
A or B
(c)

Figure 4-6. Type S pitot tube orifice alignment.

Calibration Equipment

1. Type S pitot tube assembled in the configuration anticipated for sampling. Both legs A and B permanently identified.
2. Inclined manometer with a sensitivity to 0.13 mm (0.005 in.) H_20.
3. Standard Pitot Tube
    a. Standard pitot-static tube with NBS-traceable calibration coefficient.
    b. Standard pitot-static tube constructed as shown in Figure 4-7. A pitot tube designed according to these criteria will have a baseline calibration coefficient of 0.99 ± 0.01.

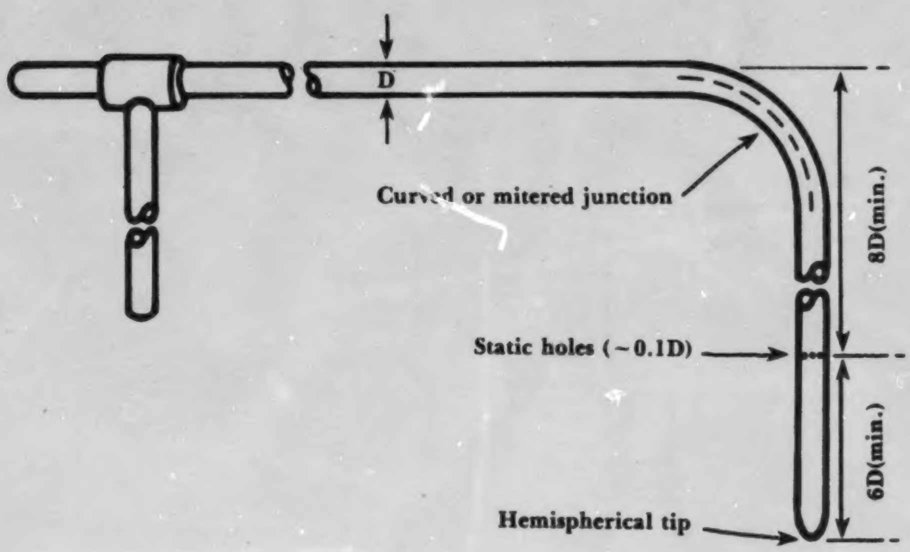


Figure 4-7. Standard Prandtl pitot static tube.

4. Calibration Duct
   - a. Minimum duct diameter cross-section must be 30.5 cm (12 inches).
   - b. Cross-section constant over a distance greater than 10 duct diameters.
   - c. Entry ports arranged so that standard pitot and Type S pitot are reading gas pressure at the same point in the duct.
   - d. Flow system capable of generating a gas velocity of approximately 915 m/min. (3000 ft./min.). The gas flow must be constant with time for steady flow. There must be no cyclonic gas flow in the duct.
   - e. If a multipoint calibration is performed, the duct gas velocity should be variable across the range of 180 to 1525 m/min (600 to 5000 ft./min.).
5. Support system to assure that pitot alignment is level and parallel to the duct axis.
6. Tubing and quick connection fittings.
7. Barometer.

Calibration Procedures

The duct gas flow system should be established at a steady flow rate and should be checked to insure that there is no cyclonic gas flow. The pressure differential gage should be thoroughly checked for proper zero, level, fluid density, and volume, and it should be set up on an area free of vibration. The pitot tube lines should be arranged so that they may be easily and quickly switched from one pitot tube to another. Always leave manometer connections set and switch lines at the pitot tube.

1. Leak test the pitot tubes and tubing by sealing the pitot tube impact opening and then establishing a positive pressure at the opening greater than 7.6 cm (3 in.). The manometer pressure should remain stable for at least 15 seconds. Repeat the procedure for the static pressure side of the pitot tube, using *negative* pressure. Perform this check for all pitot tubes used in the calibration.
2. Using the standard pitot tube, measure the gas velocity pressure at the center of the calibration duct. Simultaneously, measure gas temperature. The sensing orifice must be parallel to the duct axis and perpendicular to the gas flow (Figure 4-8).

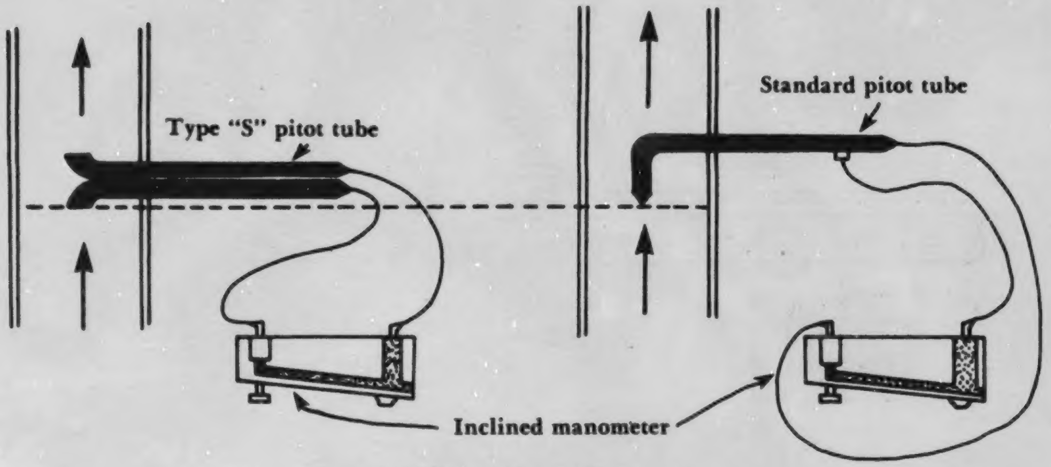


Figure 4-8. Pitot tube position in duct.

The standard pitot tube entry port should be sealed around the tube, with no sealing material protruding into the duct, and the Type S pitot tube port should be sealed.

3. Record all data (Figure 4-10), and then disconnect the standard pitot tube from the differential pressure gage, remove the tube from the duct, and seal the port.
4. Assemble the Type S pitot tube and accessories to minimize aerodynamic interferences (Figure 4-9).

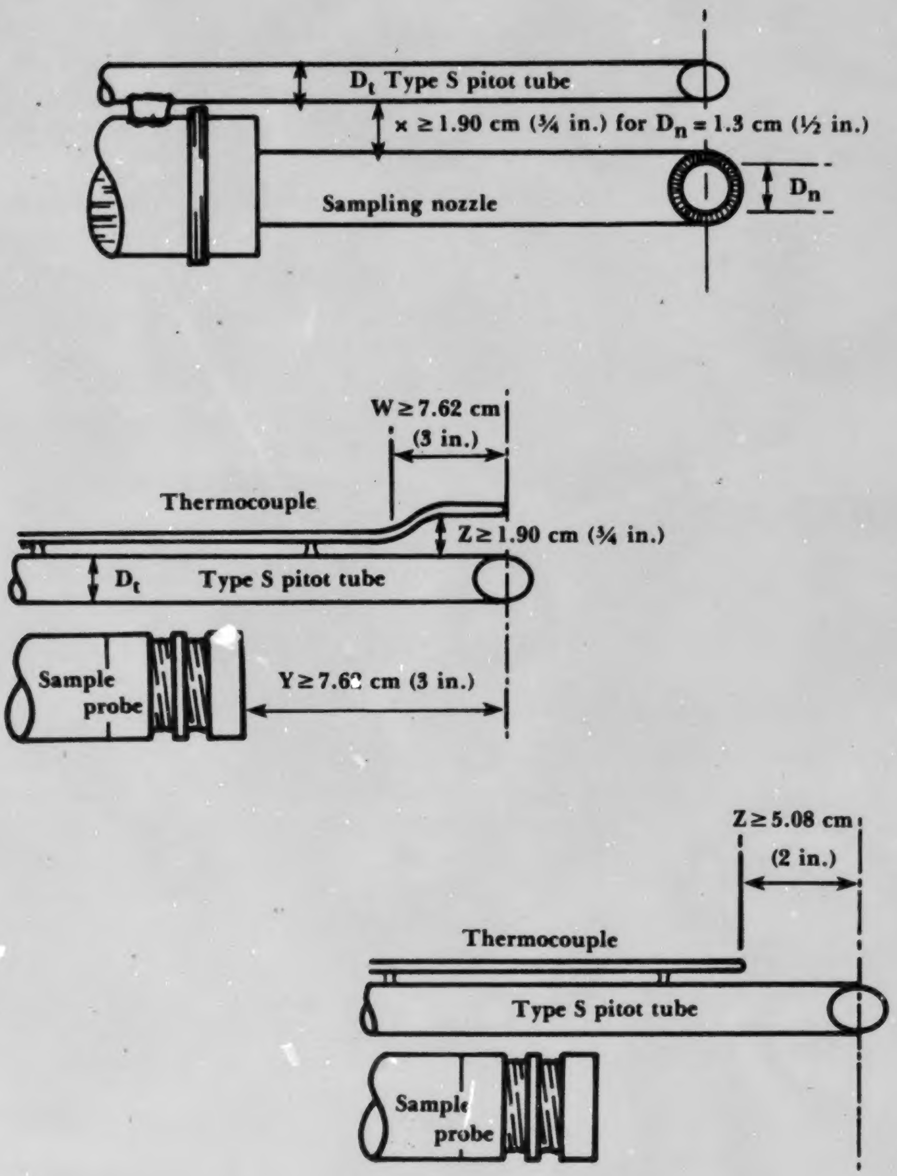

D_t Type S pitot tube
x ≥ 1.90 cm (¾ in.) for D_n = 1.3 cm (½ in.)
Sampling nozzle
D_n
W ≥ 7.62 cm (3 in.)
Thermocouple
Z ≥ 1.90 cm (¾ in.)
D_t
Type S pitot tube
Sample probe
Y ≥ 7.62 cm (3 in.)
Z ≥ 5.08 cm (2 in.)
Thermocouple
Type S pitot tube
Sample probe

Figure 4-9. Configurations for minimum interference.

A very large sampling assembly can disturb the gas flow in small ducts. If the area of the assembled probe-pitot tube is greater than 2 percent of the duct cross-sectional area, the assembly should be calibrated in a larger test section, or the C_p should be corrected for blockage (see 40 *CFR* 60.46, paragraphs a-f).

5. Connect the Type S pitot tube to the differential pressure gage and insert the tube assembly into the duct. The Type S pitot tube must measure the gas velocity pressure at the same point in the duct as the standard pitot tube, and the pitot leg A must be properly aligned to the gas flow (Figure 4-8). Seal around the Type S pitot tube, then record all data (Figure 4-10) .
6. Repeat the preceding steps until three readings have been made for leg A. Calibrate leg B in the same way. Calculate the pitot tube coefficient by the equation

(Eq.4-1)

$$C_{p(s)} = C_{p(std)}\sqrt{\frac{\Delta p_{std}}{\Delta p_s}}$$

where

$C_{p(s)}$ = Type S pitot tube coefficient
$C_{p(std)}$ = standard pitot tube coefficient
Δp_{std} = velocity head measured by the standard pitot tube, cm H_20 (in. H_20)
Δp_s = velocity head measured by the Type S pitot tube, cm H_20 (in. H_20).

The deviation of each $C_{p(s)}$ from the average $(\overline{C}_p)$ is calculated by $C_{p(s)} - C_{p\,(leg\ A\ or\ B)}$. Average deviation from the mean for leg A or B is calculated by the equation

(Eq.4-2)

$$\sigma = \frac{\sum_{1}^{3} |C_{p(s)} - \overline{C}_{p(A\ or\ B)}|}{3}$$

σ must be ≤ 0.01 for the test to be acceptable. $|C_{p(side\ A} - C_{P(side\ B)}|$ must also be ≤ 0.01 if the average of $C_{p(side\ A)}$ and $C_{p(side\ B)}$ is to be used.

PITOT TUBE CALIBRATION

Pitot tube calibration number ____________________ Date ____________________

Calibrated by ____

A Side Calibration

Run No.	Δp_{std} cm H_20 (in. H_20)	Δp_s cm H_20 (in. H_20)	$C_{p(s)}$	Deviation $C_{p(s)}-\bar{C}_{p(A)}$
1				
2				
3				
		$\bar{C}_{p(\text{side A})}$		

B Side Calibration

Run No.	Δp_{std} cm H_20 (in. H_20)	Δp_s cm H_20 (in. H_20)	$C_{p(s)}$	Deviation $C_{p(s)}-\bar{C}_{p(B)}$
1				
2				
3				
		$\bar{C}_{p(\text{side B})}$		

Figure 4-10. Pitot tube calibration data.

BAROMETER CALIBRATION

The field barometer should be calibrated against a laboratory mercury barometer before each field use. If the field barometer can not be adjusted to read within 5.1 mm (0.2 in.) Hg of the laboratory barometer, it should be repaired or replaced. The field barometer should be well-protected during travel.

CALIBRATION OF A STANDARDIZED DRY GAS METER

Reference volume meters are expensive for the average source sampling laboratory. An inexpensive dry gas test meter calibrated against a reference volume meter is accurate and convenient. This standardized test meter may then be used to calibrate sampling console dry gas meters.

Calibration Equipment

1. Spirometer.
2. Dry gas test meter (0.1 cubic ft./meter revolution). This must be a *test* meter to assure sufficient accuracy.
3. Oil manometer (0-2 inches H_2O).
4. Leak-free pump (lubricated fiber vane pump with appropriate oil traps or diaphragm pump with gas pulse compensating baffle).
5. Needle valve.
6. Three-way valve.
7. Two dial thermometers capable of reading gas temperature ± 2°F.

Calibration Procedures

Possible equipment configurations for dry gas meter calibration are shown as Figure 4-11.

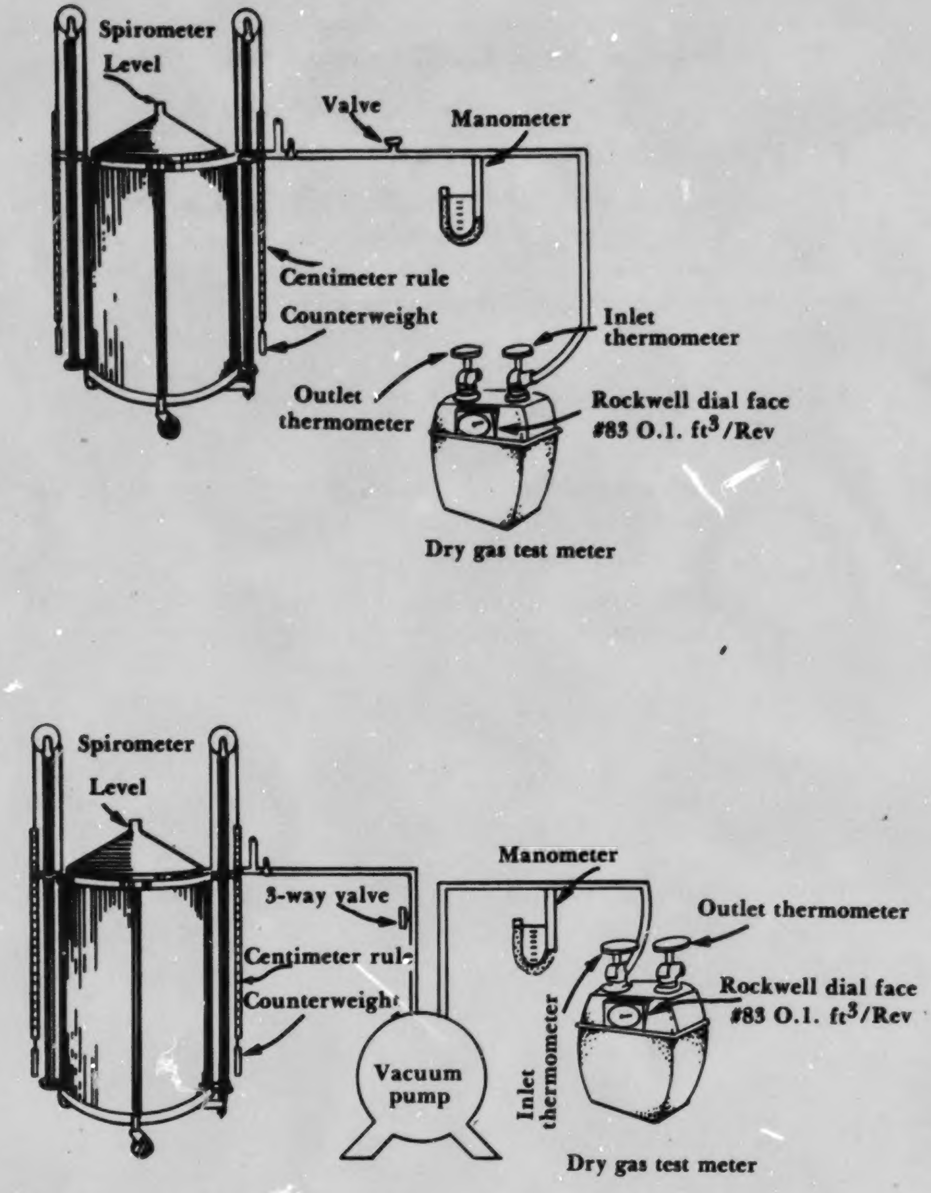

Spirometer
Level
Valve
Manometer
Centimeter rule
Counterweight
Inlet thermometer
Outlet thermometer
Rockwell dial face #83 O.1. ft³/Rev
Dry gas test meter
Spirometer
Level
Manometer
3-way valve
Centimeter rule
Counterweight
Outlet thermometer
Rockwell dial face #83 O.1. ft³/Rev
Vacuum pump
Inlet thermometer
Dry gas test meter

Figure 4-11. Dry gas meter calibration configurations.

The meter must be calibrated at several flow rates corresponding to pressure differentials *(ΔH)* of 0.1, 0.5, 1.0, and 1.5 inches of water. The 1.5 *ΔH* may be achieved by weighting the spirometer bell or using the pump; the other *ΔH's* can be established without the pump. The pump could increase the gas temperature from the spirometer to the dry gas meter. If it does, gas volume must be corrected for a temperature increase. Calibration of the meter without a pump in the system eliminates the need for temperature corrections.

1. The calibration system should be assembled and thoroughly tested for leaks at ≥2 in H_2O. All leaks should be eliminated.
2. Level the spirometer and fill it with air. Allow the bell several minutes to stabilize.
3. Completely open the spirometer outlet valve and establish a 0.1 in. H_2O manometer reading into the dry gas meter using the gas-flow needle valve. Close the spirometer outlet valve.
4. Read the spirometer meter stick settings. Read the dry gas meter dial value.
5. Open the spirometer outlet valve, check manometer reading and allow 0.5 cubic feet of air to flow to the dry gas meter (5 revolutions of 0.1 ft.^{3}/revolution dry gas meter dial).
6. Stop the air flow. Record the dry gas meter and spirometer settings on the calibration form (Figure 4-12). Repeat the procedure for the other ΔH values. Calculate and average the dry gas meter correction factors. If the factor is outside the tolerance 1 ± 0.02, adjust the dry gas meter internal sliding vanes and recalibrate.

If a pump is used in the calibration apparatus, it could heat the gas entering the dry gas meter. This possibility requires that the dry gas meter volume be corrected to conditions in the spirometer by the equation

(Eq.4-3)

$$V_{m(corr)} = V_m \left[\frac{T_{amb} \left(P_b + \frac{\Delta H}{13.6} \right)}{P_b \, T_{m\,(avg)}} \right]$$

When a pump is used, a three-way valve is employed to establish the flow rate through the dry gas meter, using atmospheric air. The valve is switched to the spirometer, and the dry gas meter is read.

CALIBRATION OF THE SOURCE SAMPLING NOMOGRAPH

A number of nomographs are available commercially. These instruments are used to solve graphically the sampling nozzle sizing equation

STANDARDIZED DRY GAS METER CALIBRATION

Name________________ Date________________

Ambient Temperature ________________ Barometric Pressure ________________

Dry Gas Test Meter No. ________________ Correction Factor (DGMCF) ________________

Spirometer Displacement Factor ________________

Manometer	Spirometer Volume (V_{spir})	Dry Gas Meter Volume (V_m)	Dry Gas Meter Correction Factor
0.1 in. H_20	Final______ Initial ______ Displacement ____ Volume (V_{spir})____	Final______ Initial ______ Volume (V_m)____ T_m ______	
0.5 in. H_20	F ______ I______ D ______ V_{spir}______	F ______ I______ V_m ______ T_m ______	
1.0 in. H_20	F ______ I______ D ______ V_{spir}______	F ______ I______ V_m ______ T_m ______	
1.5 in. H_20	F ______ I______ D ______ V_{spir}______	F ______ I______ V_m ______ T_m ______	
			Average DGMCF

Spirometer Volume *(V_{spir})
displacement (cm) × displacement factor (liters/cm) = V_{spir} liters

Dry Gas Meter Correction Factor (DGMCF)

$$\frac{V_{spir}}{V_m} = \text{DGMCF}$$

Average Dry Gas Test Meter Correction Factor Tolerance SV/DV = 1 ± 0.02

---

*0.03431 cubic feet/liter
(liters)(.03431 $ft.^3$/liter) = $ft.^3$

Figure 4-12. Form for standardized dry gas meter calibration.

(Eq.4-4)

$$D_n = \sqrt{\frac{0.0358\ Q_m\ P_m}{T_m\ C_p(1 - B_{ws})}\ \sqrt{\frac{T_s\ M_s}{P_s \bar{\Delta p}}}}$$

where

D_n = *nozzle diameter (in.)*
Q_m = *volumetric flow rate through meter* (ft^3)
P_m = *absolute pressure at meter (in. Hg)*
P_s = *absolute pressure at stack (in. Hg)*
T_m = *absolute temperature at meter (°R)*
T_s = *absolute temperature at stack (°R)*
C_p = *pitot tube calibration coefficient*
B_{ws} = *water vapor in stack gas, volume fraction*
M_s = *molecular weight of stack gas, wet basis (lb/lb-mole)*
$\bar{\Delta p}$ = *average velocity head of stack gas (in.* H_2O*)*

and the isokinetic rate equation

(Eq.4-5)

$$\Delta H = \left[846.72\ D_n^4\ \Delta H_@\ C_p^2\ (1 - B_{ws})^2\ \frac{M_d\ T_m\ P_s}{M_s\ T_s\ P_m}\right] \Delta p$$

Today, programmable calculators are often being used to solve these equations. Also, a number of plastic slide rules are currently available. These are somewhat more accurate and more convenient to use than the traditional source sampling nomograph.

If a nomograph is used, it should be thoroughly checked for scale accuracy and alignment. Nomograph calibration forms (Figure 4-13) help in making these checks. The traditional source sampling nomograph assumes that the Type S pitot tube has a C_p of .85. For C_p values different from .85, the C-factor obtained on the nomograph must be adjusted by the method given in Form A (Figure 4-12).

The traditional source sampling nomograph also assumes that the molecular weight of the stack gas is 29.1 lb/lb-mole. For molecular weights appreciably different from this value, the C factor of the nomograph should be further adjusted by the method given in Form B.

Traditional source sampling nomographs are usually made by fixing a decal on a plastic board. Unfortunately, the scales printed on the decal frequently become misaligned when the decal is applied to the board. Form C gives a procedure which one can use to check the nomograph alignment. The calibration form gives the values used to check the alignments. The check is accomplished by positioning the marker line through the ΔH and Δp points given, and then tightening the pivot point. The ΔH reading for each Δp value given is then read. If any ΔH readings are off-scale or differ by more than 3% of the proper values, the scale is misaligned. Nomographs which indicate such misalignment should be returned to the manufacturer and replaced.

SOURCE SAMPLING NOMOGRAPH CALIBRATION DATA

Form A. Correct the C-Factor obtained in normal operation of the nomograph for $C_p \neq 0.85$ by:

$$\text{C-Factor (Adjusted)} = (\text{C-Factor Nomograph}) \frac{(\text{Pitot Tube } C_p)^2}{(0.85)^2}$$

Nomograph ID. No.	Nomograph C-Factor	Pitot C_p	$\frac{(C_p)^2}{(0.85)^2}$	Adjusted C-Factor

Form B. Correct the Nomograph C-Factor for $M_d \neq 29$ lb/lb-mole

$$\text{C-Factor (Adjusted)} = (\text{C-Factor Nomograph}) \frac{1-B_{ws} + 18\ B_{ws}/29}{1-B_{ws} + 18\ B_{ws}/M_d}$$

Nomograph ID. No.	Nomograph C-Factor	Stack Gas Dry Molecular Weight (M_d)	Adjusted C-Factor

Form C. Scale Alignment (Check all Nomographs)

	Step 1	Step 2	Step 3		
	Set marker on and tighten pivot	Set one end of marker on	ΔH should read	Nomograph ID. No._____ actual ΔH reading	Nomograph ID. No._____ actual ΔH reading
Alignment Test 1	ΔH = 0.1	Δp = 0.01	1.0		
	Δp = 0.001	Δp = 0.1	10.0		
Alignment Test 2	ΔH = 10.0	Δp = 1.0	1.0		
	Δp = 10.0	Δp = 0.1	.1		
Alignment Test 3	ΔH = 1.0	Δp = 1.0	10.0		
	Δp = 0.1	Δp = 0.01	.1		

Form D. Nomograph Accuracy*

Meter Console $\Delta H_@$	Meter T_m °F	Stack Gas $B_{ws} \times 100$	P_s	P_m	Stack T_s °F	$\overline{\Delta p}$	Nomograph C-Factor	Calculated Nozzle D_n	Nomograph ΔH	Calculated ΔH
1.84*	70	5	29.92	29.92	1000	1.00				
1.00	140	10	29.92	29.92	300	2.00				
2.00*	100	30	35.9	29.92	500	2.00				

*Assume $Q_m = 0.75$; $C_p = 0.85$; $B_{wm} = 0$; $M_d = 29.0$

Figure 4-13. Forms for source sampling nomograph calibration.

Form D gives a procedure for checking the accuracy of the nomograph. Here the true values obtained by using the equations given above are compared to the values obtained by the nomograph manipulations. Calculated and nomograph values should not differ by more than 5%. Nomographs showing greater error should be returned to the manufacturer and replaced.

CALIBRATION OF THE PROBE NOZZLE DIAMETER

The probe nozzle should be made of 316 stainless steel or quartz with a sharp, tapered leading edge. A taper angle of ≤ 30° on the outside of the sampling nozzle will preserve a constant internal diameter. The nozzle should be a button-hook or elbow design so that the nozzle opening is below the pitot tube sensing orifice. This is necessary for isokinetic sampling. Alternate construction materials or nozzle shapes must be approved by the administrator.

The sampling nozzle must be calibrated before use in a source experiment. Calibration should be done in the laboratory and checked just prior to use in the field. Inside/outside calipers are used to measure the interior nozzle diameter to the nearest 0.025 mm (0.001 in.).

The calipers are inserted as close to the edge of the nozzle opening as possible; readings are then taken on three separate diameters and recorded. Each reading must agree within 0.1 mm (0.004 in.), or the nozzle must be reshaped. Any nozzle that has been nicked, dented, or corroded must be reshaped and recalibrated. All calibrated nozzles should be permanently identified.

Chapter 5

The Source Test

A source sampling experiment provides data on source emissions parameters. The isokinetic source test extracts a representative gas sample from a gas stream. Although often used only to determine compliance with emissions regulations, the test data can also provide information useful in evaluating control equipment efficiency or design, process economics, or process control effectiveness. Valid source sampling experiments, therefore, yield valuable information to both the industrial and environmental engineer.

The source test is an original scientific experiment and should be organized and executed with the same care taken in performing any analytical experiment. This requires that objectives be decided before starting the experiment and that the procedures and equipment be designed to aid in reaching those objectives. The quantitative or qualitative analysis of the source sample should be incorporated as an integral part of the source test. After all work is done, the results should be evaluated to determine whether objectives have been accomplished. This section contains flow charts and descriptions to assist in the design, planning, and performance of the source test described.

Source Test Objectives

The essential first step in all experiments is the statement of objectives. The source test measures a variety of stack gas variables which are used in evaluating several characteristics of the emissions source. The source experiment should be developed with techniques and equipment specifically designed to give complete, valid data relating to these objectives. Approaching the experiment in this manner increases the possibilities of a representative sampling of the source parameters to be evaluated.

Experiment Design

A well designed experiment incorporates sampling equipment, techniques, and analysis into an integrated procedure to meet test objectives. The source sampling experiment must be based on a sampling technique that can collect the data required. The sampling equipment is then designed to facilitate the sampling procedure. The analysis of the sample taken must be an integral factor in the sampling techniques and equipment design. This approach of achieving test objectives provides the best possible source test program.

Designing a source test experiment requires a knowledge of sampling procedures and industrial processes, a thoroughly researched sampling experiment, and a good basic understanding of the process operation to be tested. This knowledge assists in determining the types of pollutants emitted and test procedures and analysis that will achieve valid, reliable test results. A literature search of the sampling problem can yield information that may help improve test results or make testing much easier.

Final Test Protocol

The final test protocol clearly defines all aspects of the test program, and incorporates the work done in research, experiment design, and the presurvey. All aspects of this test, from objectives through analysis of the sample and results of the sampling, should be organized into a unified program. This program is then explained to industrial or regulatory personnel involved. The protocol for the entire test procedure should be understood and agreed upon prior to the start of the test. A well organized test protocol saves time and prevents confusion as the work progresses.

Test Equipment Preparations

The test equipment must be assembled and checked in advance; it should be calibrated following procedures recommended in the Code of Federal Regulations and this manual. The entire sampling system should be assembled as intended for use during the sampling experiment. This assures proper operation of all the components and points out possible problems that may need special attention during the test. This procedure will assist in making preparations and planning for spare parts. The equipment should then be carefully packed for shipment to the sampling site.

The proper preparation of sampling train reagents is an important part of getting ready for the sampling experiment. The Method 5 sampling train requires well identified, precut, glass mat filters that have been desiccated to a constant weight. These tare weights must be recorded to ensure against errors. Each filter should be inspected for pinholes that could allow particles to pass through. The acetone (or other reagent) used to clean sampling equipment must be a low residue, high purity solvent stored in glass containers. Silica gel desiccant should be dried at 250° to 300°F for 2 hours, then stored in air-tight containers; be sure the indicator has not decomposed (turned black). It is a good procedure, and relatively inexpensive, to use glass-distilled, dionized water in the impingers. Any other needed reagents should be carefully prepared. All pertinent data on the reagents, tare weights, and volumes should be recorded and filed in the laboratory with duplicates for the sampling team leader.

Testing at the Source

The first step in performing the source test is establishing communication among all parties involved in the test program. The source sampling test team should notify the plant and regulatory agency of their arrival. All aspects of the plant operation and sampling experiment should be reviewed and understood by those involved. The proper plant operating parameters and sampling experiment procedures should be recorded in a test log for future reference. The sampling team is then ready to proceed to the sampling site.

The flow diagram outlines the procedures for performing the stack test. The items given are for a basic Method 5 particulate sample. Each item is explained in various sections of this manual. The laboratory training sessions given in Course 450 help to organize the Method 5 test system.

The flow diagram should be of assistance to those having completed the 450 course curriculum and can also serve as a useful guide to anyone performing a stack test.

METHODS FOR SETTING THE ISOKINETIC FLOW RATE IN THE METHOD 5 SAMPLING TRAIN

The commercially available nomograph is often used for the solution of the isokinetic rate equation. These nomographs have based the solution of the isokinetic equation upon the assumptions that the pitot tube coefficient will be 0.85, the stack gas dry molecular weight will be 29.0 lb/lb-mole and will only vary with a change in stack gas moisture content in addition to relying on the use of a drying tube in the train. The nomograph also assumes that changes in other equation variables will be insignificant. Many purchasers are unaware of these assumptions or manufacturer construction errors and use the device without calibrating it or verifying its accuracy. Procedures are presented here to ascertain the precision of nomograph construction and its accuracy. The basic equations employed in constructing a nomograph are given and a calibration form is provided (See Calibration chapter, page 4-17).

The derivation of the isokinetic rate equation is given in Appendix C. The equation is:

(Eq.5-1) $$\Delta H = \left[846.72 \, D_n^4 \, \Delta H_@ \, C_p^2 \, (1 - B_{ws})^2 \, \frac{M_d \, T_m \, P_s}{M_s \, T_s \, P_m} \right] \Delta p$$

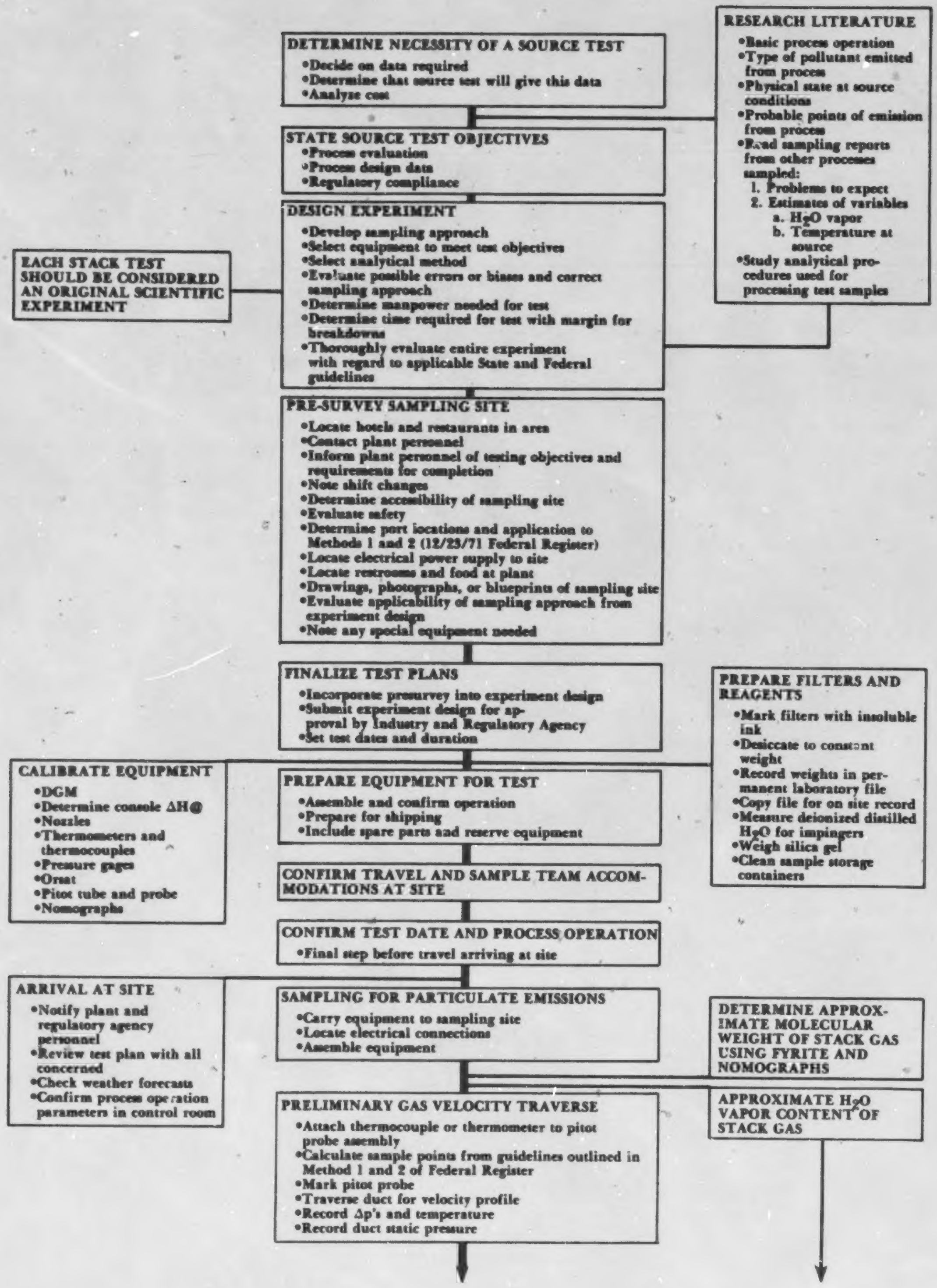
where

C_p = *pitot tube coefficient*
D_n = *nozzle diameter (in.)*
ΔH = *pressure difference of orifice meter (in.* H_2O*)*
$\Delta H_@$ = *orifice meter coefficient,* ΔH *for 0.75 cfm at* $STP = 0.9244/K_m^2$ *(in.* H_2O*)*
M_s = *apparent stack gas molecular weight* $= M_d(1 - B_w) + 18B_w$ *(lb/lb-mole)*
M_d = *dry gas molecular weight (29) for dry air (lb/lb-mole)*
P_s = *absolute stack pressure (in. Hg)*
P_m = *meter absolute pressure (in. Hg)*
Δp = *pressure difference of pitot tube (in.* H_2O*)*
T_m = *absolute meter temperature* = °R = °F + 460°

isokinetic $\Delta H = K \Delta p$

K = *Reduced terms in the isokinetic equation.*

Figure 5-1. Planning and performing a stack test.



DETERMINE NECESSITY OF A SOURCE TEST
- Decide on data required
- Determine that source test will give this data
- Analyze cost

RESEARCH LITERATURE
- Basic process operation
- Type of pollutant emitted from process
- Physical state at source conditions
- Probable points of emission from process
- Read sampling reports from other processes sampled:
  1. Problems to expect
  2. Estimates of variables
     a. H_2O vapor
     b. Temperature at source
- Study analytical procedures used for processing test samples

STATE SOURCE TEST OBJECTIVES
- Process evaluation
- Process design data
- Regulatory compliance

EACH STACK TEST SHOULD BE CONSIDERED AN ORIGINAL SCIENTIFIC EXPERIMENT

DESIGN EXPERIMENT
- Develop sampling approach
- Select equipment to meet test objectives
- Select analytical method
- Evaluate possible errors or biases and correct sampling approach
- Determine manpower needed for test
- Determine time required for test with margin for breakdowns
- Thoroughly evaluate entire experiment with regard to applicable State and Federal guidelines

PRE-SURVEY SAMPLING SITE
- Locate hotels and restaurants in area
- Contact plant personnel
- Inform plant personnel of testing objectives and requirements for completion
- Note shift changes
- Determine accessibility of sampling site
- Evaluate safety
- Determine port locations and application to Methods 1 and 2 (12/23/71 Federal Register)
- Locate electrical power supply to site
- Locate restrooms and food at plant
- Drawings, photographs, or blueprints of sampling site
- Evaluate applicability of sampling approach from experiment design
- Note any special equipement needed

FINALIZE TEST PLANS
- Incorporate presurvey into experiment design
- Submit experiment design for approval by Industry and Regulatory Agency
- Set test dates and duration

CALIBRATE EQUIPMENT
- DGM
- Determine console ΔH@
- Nozzles
- Thermometers and thermocouples
- Pressure gages
- Orsat
- Pitot tube and probe
- Nomographs

PREPARE EQUIPMENT FOR TEST
- Assemble and confirm operation
- Prepare for shipping
- Include spare parts and reserve equipment

PREPARE FILTERS AND REAGENTS
- Mark filters with insoluble ink
- Desiccate to constant weight
- Record weights in permanent laboratory file
- Copy file for on site record
- Measure deionized distilled H_2O for impingers
- Weigh silica gel
- Clean sample storage containers

CONFIRM TRAVEL AND SAMPLE TEAM ACCOMMODATIONS AT SITE

CONFIRM TEST DATE AND PROCESS OPERATION
- Final step before travel arriving at site

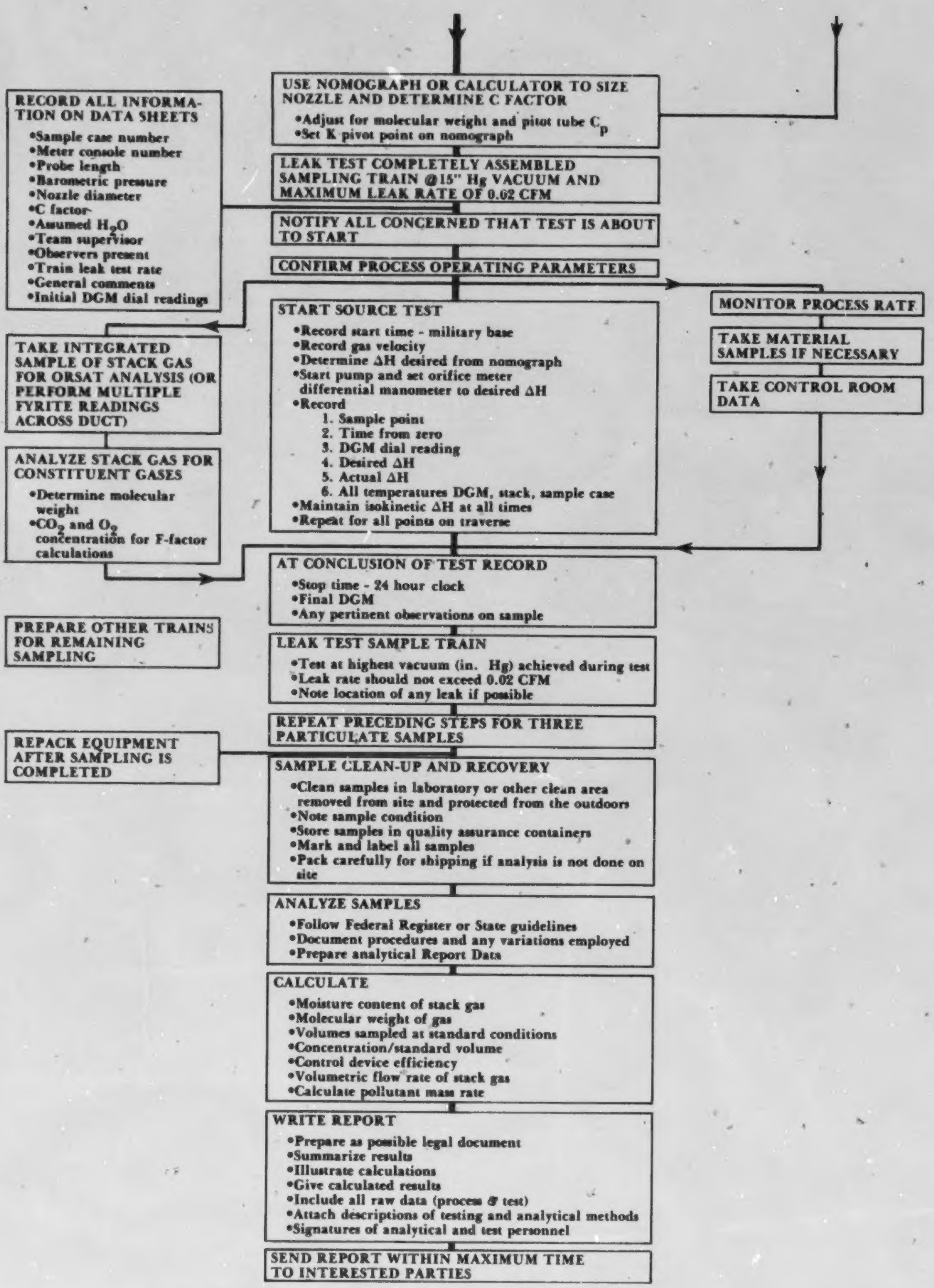
ARRIVAL AT SITE
- Notify plant and regulatory agency personnel
- Review test plan with all concerned
- Check weather forecasts
- Confirm process operation parameters in control room

SAMPLING FOR PARTICULATE EMISSIONS
- Carry equipment to sampling site
- Locate electrical connections
- Assemble equipment

DETERMINE APPROXIMATE MOLECULAR WEIGHT OF STACK GAS USING FYRITE AND NOMOGRAPHS

PRELIMINARY GAS VELOCITY TRAVERSE
- Attach thermocouple or thermometer to pitot probe assembly
- Calculate sample points from guidelines outlined in Method 1 and 2 of Federal Register
- Mark pitot probe
- Traverse duct for velocity profile
- Record Δp's and temperature
- Record duct static pressure

APPROXIMATE H_2O VAPOR CONTENT OF STACK GAS



USE NOMOGRAPH OR CALCULATOR TO SIZE NOZZLE AND DETERMINE C FACTOR

- Adjust for molecular weight and pitot tube C_p
- Set K pivot point on nomograph

RECORD ALL INFORMATION ON DATA SHEETS

- Sample case number
- Meter console number
- Probe length
- Barometric pressure
- Nozzle diameter
- C factor
- Assumed H_2O
- Team supervisor
- Observers present
- Train leak test rate
- General comments
- Initial DGM dial readings

LEAK TEST COMPLETELY ASSEMBLED SAMPLING TRAIN @15" Hg VACUUM AND MAXIMUM LEAK RATE OF 0.02 CFM

NOTIFY ALL CONCERNED THAT TEST IS ABOUT TO START

CONFIRM PROCESS OPERATING PARAMETERS

START SOURCE TEST

- Record start time - military base
- Record gas velocity
- Determine ΔH desired from nomograph
- Start pump and set orifice meter differential manometer to desired ΔH
- Record
  1. Sample point
  2. Time from zero
  3. DGM dial reading
  4. Desired ΔH
  5. Actual ΔH
  6. All temperatures DGM, stack, sample case
- Maintain isokinetic ΔH at all times
- Repeat for all points on traverse

TAKE INTEGRATED SAMPLE OF STACK GAS FOR ORSAT ANALYSIS (OR PERFORM MULTIPLE FYRITE READINGS ACROSS DUCT)

ANALYZE STACK GAS FOR CONSTITUENT GASES

- Determine molecular weight
- CO_2 and O_2 concentration for F-factor calculations

MONITOR PROCESS RATE

TAKE MATERIAL SAMPLES IF NECESSARY

TAKE CONTROL ROOM DATA

AT CONCLUSION OF TEST RECORD

- Stop time - 24 hour clock
- Final DGM
- Any pertinent observations on sample

PREPARE OTHER TRAINS FOR REMAINING SAMPLING

LEAK TEST SAMPLE TRAIN

- Test at highest vacuum (in. Hg) achieved during test
- Leak rate should not exceed 0.02 CFM
- Note location of any leak if possible

REPEAT PRECEDING STEPS FOR THREE PARTICULATE SAMPLES

REPACK EQUIPMENT AFTER SAMPLING IS COMPLETED

SAMPLE CLEAN-UP AND RECOVERY

- Clean samples in laboratory or other clean area removed from site and protected from the outdoors
- Note sample condition
- Store samples in quality assurance containers
- Mark and label all samples
- Pack carefully for shipping if analysis is not done on site

ANALYZE SAMPLES

- Follow Federal Register or State guidelines
- Document procedures and any variations employed
- Prepare analytical Report Data

CALCULATE

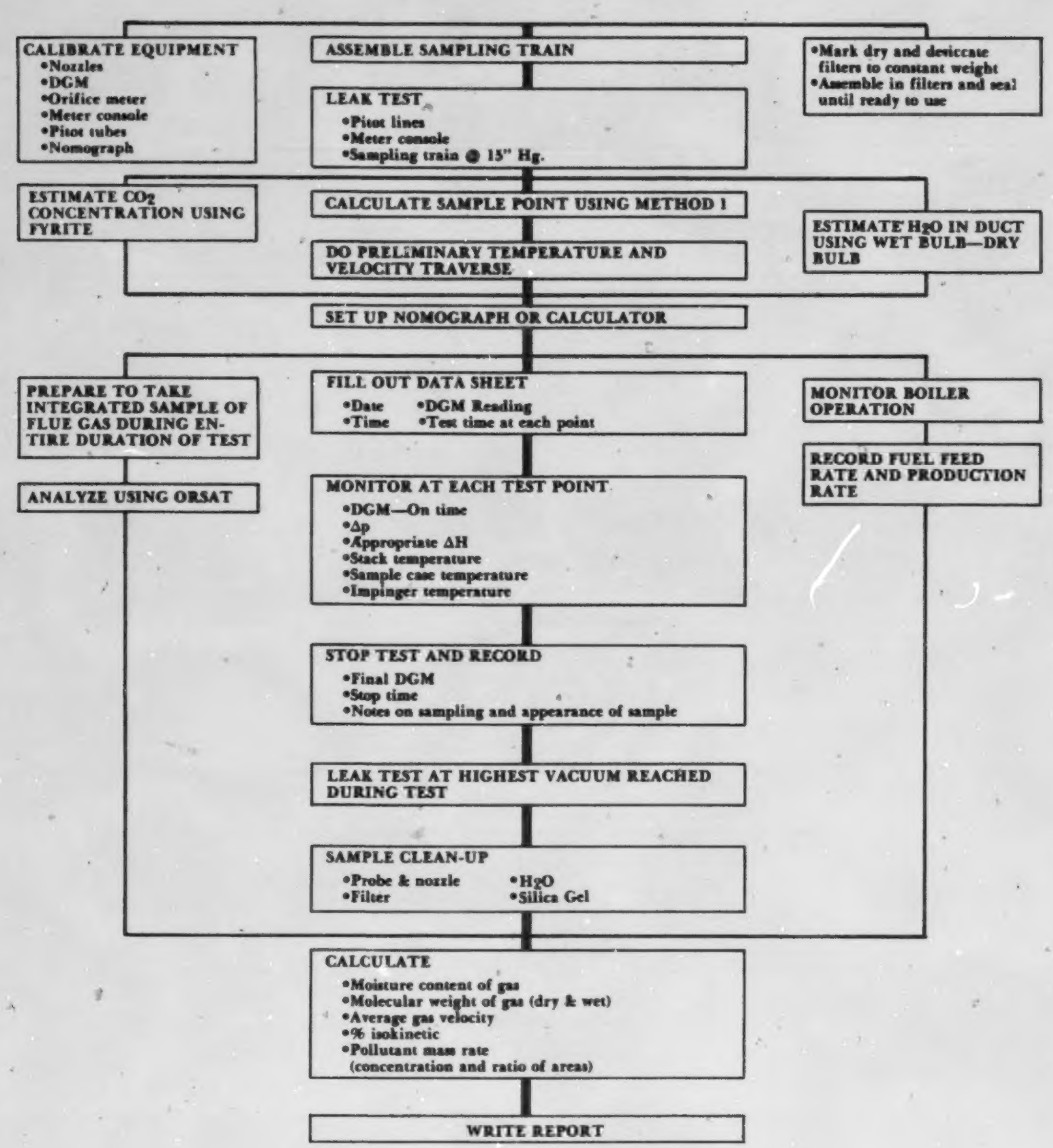
- Moisture content of stack gas
- Molecular weight of gas
- Volumes sampled at standard conditions
- Concentration/standard volume
- Control device efficiency
- Volumetric flow rate of stack gas
- Calculate pollutant mass rate

WRITE REPORT

- Prepare as possible legal document
- Summarize results
- Illustrate calculations
- Give calculated results
- Include all raw data (process & test)
- Attach descriptions of testing and analytical methods
- Signatures of analytical and test personnel

SEND REPORT WITHIN MAXIMUM TIME TO INTERESTED PARTIES

Figure 5-2. Source test outline.


CALIBRATE EQUIPMENT
•Nozzles
•DGM
•Orifice meter
•Meter console
•Pitot tubes
•Nomograph
ASSEMBLE SAMPLING TRAIN
•Mark dry and desiccate filters to constant weight
•Assemble in filters and seal until ready to use
LEAK TEST
•Pitot lines
•Meter console
•Sampling train @ 15" Hg.
ESTIMATE CO2 CONCENTRATION USING FYRITE
CALCULATE SAMPLE POINT USING METHOD 1
ESTIMATE H2O IN DUCT USING WET BULB—DRY BULB
DO PRELIMINARY TEMPERATURE AND VELOCITY TRAVERSE
SET UP NOMOGRAPH OR CALCULATOR
PREPARE TO TAKE INTEGRATED SAMPLE OF FLUE GAS DURING ENTIRE DURATION OF TEST
FILL OUT DATA SHEET
•Date
•Time
•DGM Reading
•Test time at each point
MONITOR BOILER OPERATION
RECORD FUEL FEED RATE AND PRODUCTION RATE
ANALYZE USING ORSAT
MONITOR AT EACH TEST POINT
•DGM—On time
•Δp
•Appropriate ΔH
•Stack temperature
•Sample case temperature
•Impinger temperature
STOP TEST AND RECORD
•Final DGM
•Stop time
•Notes on sampling and appearance of sample
LEAK TEST AT HIGHEST VACUUM REACHED DURING TEST
SAMPLE CLEAN-UP
•Probe & nozzle
•Filter
•H2O
•Silica Gel
CALCULATE
•Moisture content of gas
•Molecular weight of gas (dry & wet)
•Average gas velocity
•% isokinetic
•Pollutant mass rate (concentration and ratio of areas)
WRITE REPORT

The Method 5 sampling train is intended to operate at a sampling rate of 0.75 cfm of dry air at 68°F and 29.92 in. Hg. The orifice meter pressure differential that would produce such a sampling rate through the orifice is designated $\Delta H_@$.

An additional equation is necessary in order to estimate the nozzle diameter that will give a flow rate of 0.75 cfm at a reasonable pressure drop across the orifice meter.

(Eq.5-2)

$$D_n = \sqrt{\frac{0.0358\ Q_m\ P_m}{T_m\ C_p(1 - B_{ws})} \sqrt{\frac{T_s\ M_s}{P_s\ \bar{\Delta p}}}}$$

where

D_n = *nozzle diameter (in.)*
Q_m = *volumetric flow rate through meter* (ft^3)
P_m = *absolute pressure at meter (in. Hg)*
P_s = *absolute pressure at stack (in. Hg)*
T_m = *absolute temperature at meter (°R)*
T_s = *absolute temperature at stack (°R)*
C_p = *pitot tube calibration coefficient*
B_{ws} = *water vapor in stack gas, volume fraction*
M_s = *molecular weight of stack gas, wet basis (lb/lb-mole)*
Δp = *average velocity head of stack gas (in.* H_2O*)*

Once D_n is calculated, the source tester should select the nozzle in his tool box which has a value closest to that calculated. The actual nozzle used should be checked with calipers, and that value of D_n is then substituted in Equation 5-1.

Most of the variables in this equation and the isokinetic ΔH equation are known prior to sampling or can be closely estimated. Often the solution to the equation can be partially calculated before the sampling with the few remaining variables inserted and the equation quickly solved on site. The calculation of isokinetic ΔH using the derived equations allows the sampler to more quickly and easily adjust the sampling rate for changes in the stack gas variables.

SAMPLING METER CONSOLE OPERATION

The sampling meter console must be calibrated and thoroughly leak tested following the procedure given in the calibration chapter, page 4-1. Meter console operating procedures will differ somewhat according to manufacturer. The procedures discussed here will aid in operating most types of consoles. The objective is to understand console operating procedures for isokinetic source sampling.

Sampling Train Leak Tests

Completely assemble the sampling train as intended for use during the test. Turn on probe and filter heating systems and allow them to reach operating temperatures. Disconnect the umbilical cord vacuum line and turn on the meter console pump. This allows the pump to lubricate itself and to warm up (this is especially important in cold weather). Leak test the pitot tubes and lines during this warm up.

The pitot tube impact pressure leg is leak tested by applying a positive pressure. Blow into the impact opening until ≥ 7.6 cm (3 inches) H_20 is indicated by the differential pressure gage. Seal the impact opening. The pressure should be stable for at least 15 seconds. The static pressure leg of the pitot tube is leak tested in a similar way by drawing a negative pressure ≥ 7.6 cm H_20. Correct any leaks.

The sampling train is leak tested when it has reached operating temperature. Turn off the console pump; connect the umbilical vacuum line. With the coarse control value completely off, turn the fine adjustment (bypass) valve completely counterclockwise. Plug the nozzle inlet and turn on the console pump. Slowly turn the coarse adjustment valve fully open. Gradually turn the fine adjustment valve clockwise until 380 mm (15 inches) Hg vacuum appears on the vacuum gage. If this vacuum is exceeded, do *not* turn the fine adjustment valve back counterclockwise; proceed with the leak test at the vacuum indicated or slowly release the nozzle plug and restart the leak test. At the desired vacuum observe the dry gas meter pointer. Using a stopwatch, time the leak rate for at least 60 seconds. The maximum allowable leak is 0.00057 m^3/min. (0.02 cfm). Having determined the leak rate, slowly release the nozzle plug to bleed air into the train; when the vacuum falls below 130 mm(5 inches) Hg, turn the coarse adjustment valve completely off. If the leak test is unacceptable, trace all sections of the sampling train from the filter holder inlet back. (i.e., leak test from the filter inlet, then the first impinger, etc.) until the leak is found. Correct the leak and retest. Leak test at the highest vacuum reached during the test after the completing the sampling procedure. Testing for leaks should also be done any time the train is serviced (i.e., filter holder change). Record all dry gas meter readings and leak rates for each leak test.

Train Operation

When the leak tests are completed, the sampling console should be prepared for sampling. The sampling console differential pressure gages for the pitot tubes and orifice meter should be checked. Zero and level the gages as required. If the console does not use oil manometers, the gages must agree with an oil manometer within 5 percent for at least 3 Δp readings taken in the stack. This check should be done before testing. Oil manometers should be periodically leveled and re-zeroed during the test if they are used in the console.

The console operator should then determine the source variables used in solving the isokinetic rate equation. The isokinetic ΔH may be determined by using a nomograph, an electronic calculator, or a source sampling slide rule. The variables that need to be determined are: stack gas moisture content, average gas velocity pressure (Δp), stack gas temperature, and estimated average console dry gas meter temperature. The stack gas moisture can be determined by Reference Method 4 sampling or estimated with a wet bulb-dry bulb thermometer technique. The average Δp and stack gas temperature are determined by a preliminary stack traverse. The dry gas meter average temperature can be estimated to be 10°C (25° – 30°F) greater than the ambient temperature at the site. These values are then used in the nomograph or calculator to find the isokinetic ΔH.

The operator can now set up the sampling data sheet. Record the dry gas meter initial reading. Position sampling train at the first sampling point; read the pitot tube Δp and calculate the corresponding ΔH. Record starting time of the test. Turn on the console pump and open the coarse sampling valve while simultaneously starting a stopwatch. Adjust ΔH to the proper value using the fine adjustment valve. Check temperatures and record all data on the data sheet.

The sampling train should be moved to the next sampling point about 15 seconds before the time at point one is over. This allows the pitot tube reading to stabilize. The dry gas meter volume at the point sampled is read when the stopwatch shows the point sample time is over. The operator should quickly read the Δp and calculate ΔH for the next point, then set the proper sampling rate. Record all data and proceed as described for all points on the traverse. At the end of the test, close the coarse valve, stop the pump, and record the stop time. Record the final dry gas meter reading. Remove the sampling train from the stack and test the system for leaks. Record the leak rate. After the train has cooled off, proceed to the cleanup area.

SAMPLING CASE PREPARATION

Inspect and clean the source sampling glassware case before a sampling experiment; remove and clean the sample case glassware. Check the case for needed repairs and calibrate the filter heater. Store the case completely assembled.

Glassware

All glassware including the filter holder and frit should be disassembled and cleaned. Separate the individual glass pieces and check for breaks or cracks. Pieces needing repair are cleaned after repairs have been made. A thorough glass cleaning for simple particulate testing is done with soap and water followed by a distilled water rinse. If analytical work is to be performed on the sample water condensed, clean the glassware by soaking in a methanol-basic hydroxide (NaOH or KOH) solution with $pH \geq 9$. Glass should be left in the base solution until any stains can be easily washed away, but not any longer than 48 hours as the solution can etch the glass. The base should be rinsed away with several portions of distilled water. If ball-joint glassware is used, remove vacuum grease before cleaning with heptane, hexane, or other suitable solvent. Clean the glass frit by pulling several aliquots of HNO_3 through the glass frit with a vacuum pump. It should be rinsed at least three times with double volumes of distilled water and dried before using.

The rubber gasket surrounding the frit should be cleaned, removing any particles imbedded in the rubber, which could prevent proper sealing. The frit and gasket must be constructed such that the glass filter mat does not become compressed in the sealing area. If this is not the case, or the rubber is in poor condition, discard the frit.

The Sample Case

The sample case should be checked thoroughly for needed repairs. All handles, brackets, clamps, and electrical connections must be inspected. Insulation in both the hot and cold areas must be in good condition. The sample case should not leak water from the melting ice into the filter heating compartment. The impinger section should have protective foam padding on the bottom and a good drainage system. The drain plug should be clean.

Calibrate the heater in the filter compartment to maintain a temperature around the filter of 120° ± 14°C (248° ± 25°F)or at other temperatures as specified in the subparts of Title 40 of the Code of Federal Regulations. This calibration should be performed at several conditions (to account for seasonal weather changes) so that the filter compartment temperature can be maintained at the proper level at all times. Often during sampling the filter section is not easy to see, consequently, the filter temperature is difficult to monitor accurately. If the case is calibrated for several conditions, operators can maintain proper temperature control more closely.

Sampling Preparations

The sample case is readied for sampling by filling the impingers with water and silica gel. Impingers 1 and 2 are each filled with 100 ml of water by inserting a funnel in the side arm and slowly pouring in the water. This makes it easy to displace in the impinger and keeps the water from filling the bubbler tube. The third impinger is left dry. The fourth impinger is filled with 200-300 gm of preweighed silica gel. The silica gel must be added through the side arm. This prevents dust from collecting on greased ball joints or silica gel from being pulled up the center tube and out of the impinger. After loading the impingers, securely fasten the U-joints. Attach the probe to the sampling case and secure the filter holder in position. Allow the filter compartment and probe to reach operating temperature. Leak test the assembled train from the probe nozzle by pulling 380 mm Hg (15 in. Hg) vacuum on the system. The maximum allowable leak rate is 0.00057 m^3/min (0.02 cfm). After the leak test, fill the impinger section with ice and allow time for all temperatures to stabilize.

SAMPLING PROBE PREPARATION

The sampling probe should be thoroughly inspected before field use. Remove the glass probe liner by loosening the union at the end of the probe. Completely disassemble the probe unior and seal gasket, and inspect all the individual components

Probe Sheath and Pitot Tubes

The stainless steel probe sheath should have a small hole drilled near the end of the probe. This prevents a pressure differential inside the sheath from possibly diluting the sample with air drawn down the probe. If the hole is not there, the probe end (fitted into the sample case) should be sealed air tight. Check the weld at the swage fittings for cracks and repair if necessary. Inspect the pitot tubes for damage and proper construction details (see pitot tube calibration section). Pitot tubes should be cleaned, checked for cracks or breaks, and securely fastened to the probe sheath to prevent accidental misalignment in the stack. All pitot tubes and components must be leak tested.

Examine the union and seal gasket for wear. A stainless steel ring should be included in the union-gasket configuration for good compression and an air tight seal. If a rubber o-ring gasket is used (stack temperatures $\leq$ 350°F) it should be inspected for wear and replaced if necessary. Asbestos string gaskets must be replaced each time the union-gasket is disassembled. After inspecting the glass liner-heating element, reassemble the probe in the following manner to prevent leaks:

1. Insert glass liner through probe and swage nut;
2. Place stainless steel ring over glass with flat side facing out;
3. Fit gasket over glass liner and push onto steel ring;
4. Align glass liner end with edge of swage nut closest to pitot tube orifice openings;
5. Screw the union on finger tight;
6. Use probe wrenches to tighten the union. If too much tightening is done here, the end of the glass liner will break.

Glass Liner-Heating Element

The glass liner should be thoroughly cleaned with a probe brush, acetone, and distilled H_2O. If it will not come clean in this manner, it should be cleaned with dilute HCl or replaced. The glass liner-heating element in many sampling probes can not be separated, making thorough cleaning difficult. An easily separated liner-heater is a great advantage.

The heating element should be checked for good electrical insulation; the insulation on a frequently used probe liner heating element will eventually be worn or burned away. This can expose frayed wires, which may short against the probe sheath. These hazards can be avoided with careful inspections and repair. After thorough inspection, check the heating element in the reassembled probe. This procedure is helpful in finding problems before arrival at the sampling site. Attention should be given to the function of the electrical system and wrappings around the glass liner; these wraps help prevent electrical shorts against the probe sheath while minimizing glass liner flexing that can cause a liner break or electrical short.

Summary

A thorough probe check before a sampling experiment helps prevent field problems. Disassemble the probe and inspect all components. Make certain construction details and integrity are correct. Clean the glass liner thoroughly. Check the heating element electrical connections. Test the reassembled probe for leaks and proper heating.

CLEANING AND ANALYTICAL PROCEDURES FOR THE METHOD 5 SAMPLING TRAIN

The clean-up and analysis of the sample taken with the Method 5 Sampling Train is an integral part of the entire experiment. The precise operation of Method 5 Sampling equipment must be complemented by a careful clean-up of the train components. Analysis of the sample using approved procedures and good laboratory technique provides accurate laboratory data. Good testing at the stack must be followed by accurate analysis in the laboratory so that valid data may be presented.

Cleaning the Sampling Train

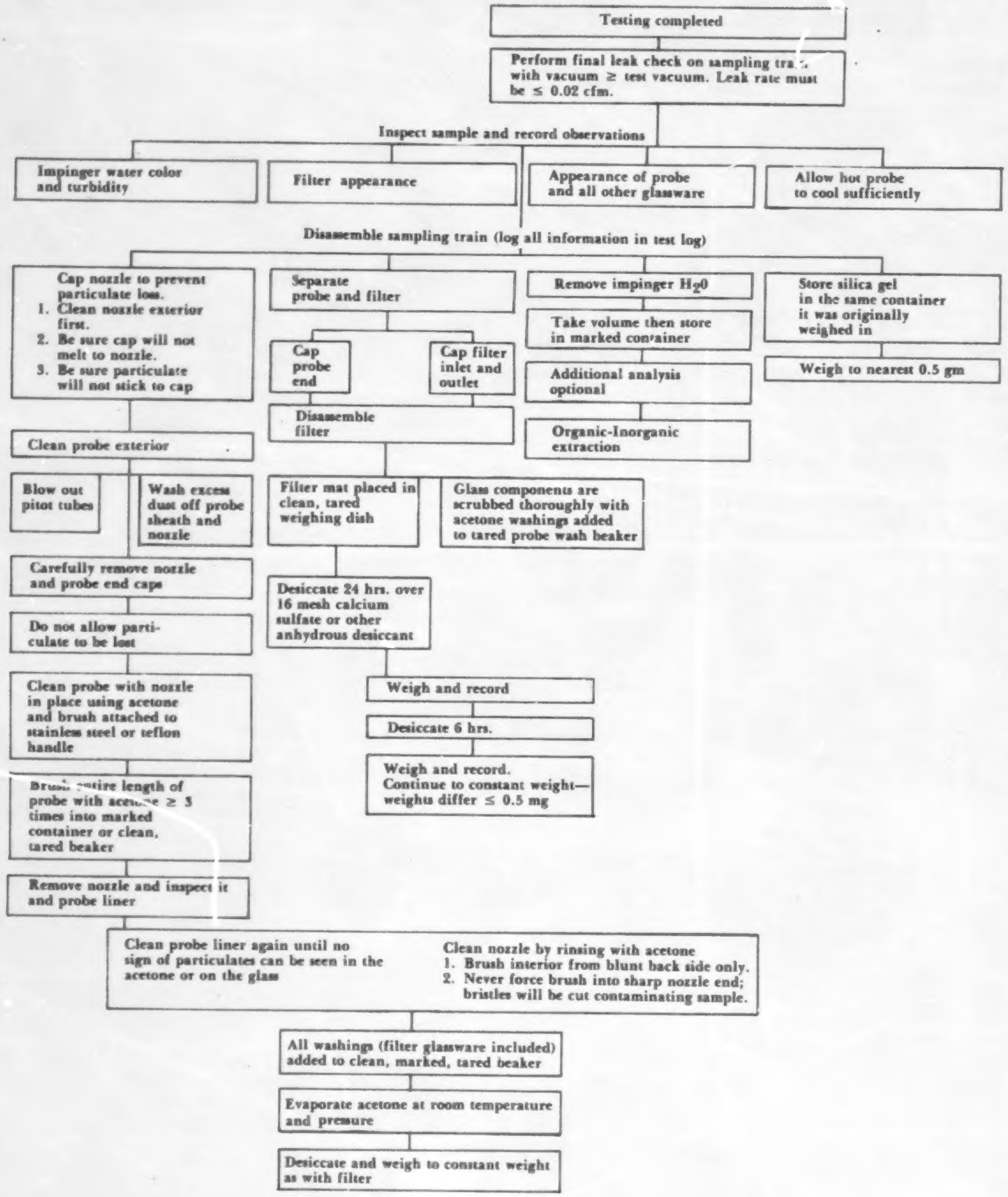
The sequence of procedures in cleaning the sampling train is best presented in an outline-flowchart form. Each step is presented with appropriate comments.

Additional Comments

The flowchart (Figure 5-3) gives the general procedure for sample clean-up. Many factors can affect the accuracy of the final sample obtained. Care and experience are very important when cleaning the sample train. A number of helpful tips are given below;

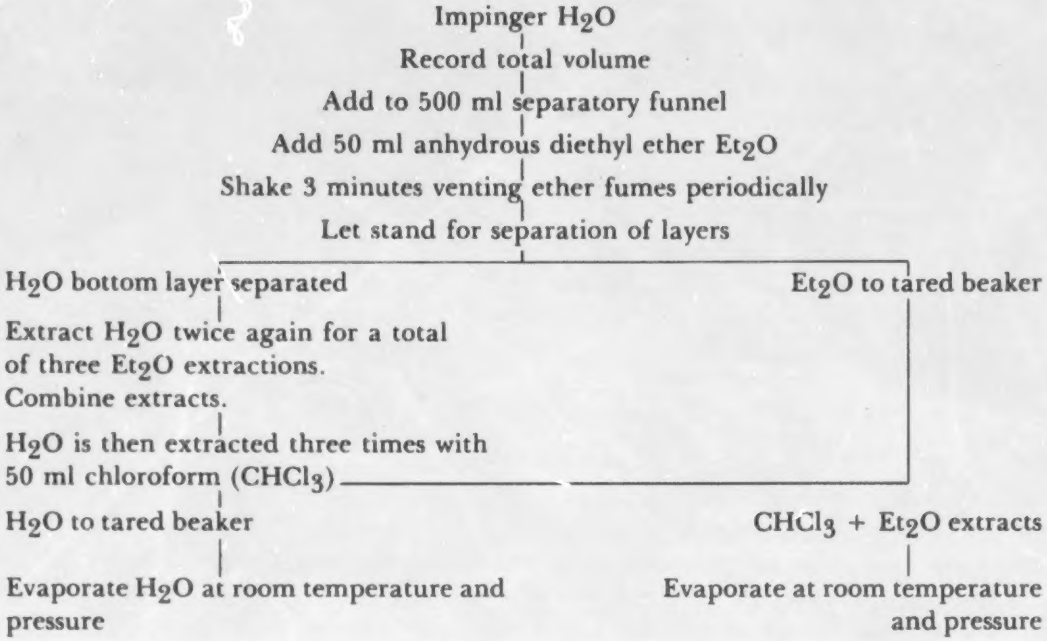
1. Always perform clean-up procedures in a clean, quiet area. The best area is a laboratory.
2. Make a probe holder for the probe cleaning procedure or be sure two people perform the procedure; this prevents spills and accidents.
3. Clean all equipment in an area where an accidental spill may be recovered without contaminating the original sample.
    a. Open and clean the filter holder over clean glassine or waxed paper so that a spill can be recovered.
    b. Clean probe into a container sitting on the same type of glassine paper.
4. Clean the probe equipment thoroughly:
    a. Brush probe a minimum of three times.
    b. Visually inspect the probe interior.
    c. Record appearance and confidence of cleanliness.
    d. Repeat brushing until cleaning is complete.
    e. Confidence ≥ 99%. Check with tared cotton swab brushed through probe.

Figure 5-3. Cleaning the sample train.


Testing completed
Perform final leak check on sampling train with vacuum ≥ test vacuum. Leak rate must be ≤ 0.02 cfm.
Inspect sample and record observations
Impinger water color and turbidity
Filter appearance
Appearance of probe and all other glassware
Allow hot probe to cool sufficiently
Disassemble sampling train (log all information in test log)
Cap nozzle to prevent particulate loss. 1. Clean nozzle exterior first. 2. Be sure cap will not melt to nozzle. 3. Be sure particulate will not stick to cap
Separate probe and filter
Remove impinger H2O
Store silica gel in the same container it was originally weighed in
Cap probe end
Cap filter inlet and outlet
Take volume then store in marked container
Weigh to nearest 0.5 gm
Additional analysis optional
Disassemble filter
Organic-Inorganic extraction
Clean probe exterior
Blow out pitot tubes
Wash excess dust off probe sheath and nozzle
Filter mat placed in clean, tared weighing dish
Glass components are scrubbed thoroughly with acetone washings added to tared probe wash beaker
Carefully remove nozzle and probe end caps
Desiccate 24 hrs. over 16 mesh calcium sulfate or other anhydrous desiccant
Do not allow particulate to be lost
Weigh and record
Clean probe with nozzle in place using acetone and brush attached to stainless steel or teflon handle
Desiccate 6 hrs.
Weigh and record. Continue to constant weight—weights differ ≤ 0.5 mg
Brush entire length of probe with acetone ≥ 3 times into marked container or clean, tared beaker
Remove nozzle and inspect it and probe liner
Clean probe liner again until no sign of particulates can be seen in the acetone or on the glass
Clean nozzle by rinsing with acetone 1. Brush interior from blunt back side only. 2. Never force brush into sharp nozzle end; bristles will be cut contaminating sample.
All washings (filter glassware included) added to clean, marked, tared beaker
Evaporate acetone at room temperature and pressure
Desiccate and weigh to constant weight as with filter

72

5. Clean filter equipment thoroughly.
    a. Brush all glassware until clean.
    b. Check with tared cotton swab.
    c. Remove all filter mats adhering to rubber seal ring. This is extremely important for accurate particulate weighing.
    d. Do not scrape glass frit into sample.
6. The laboratory scale accuracy and sensitivity should be checked before each analysis using standard weights. Actual weight and scale reading should agree to ± 0.5 mg.
7. Careful labeling of all train components, tared beakers, and sample containers avoids problems and confusion.
8. Permanently marked weighing glassware with permanent record of their new, clean, reference tare weight allows a check of cleanliness when tared just prior to use. This can also be helpful in checking any weighing discrepancies in the analysis (re-tare reference periodically).
9. Acetone is the solvent recommended for cleaning; however, water washing may be suggested by the type of pollutant sampled and should be added to the procedure if indicated.
10. Adding heat to the evaporation of solvent could evaporate volatile materials and give erroneous data.
11. The laboratory must have:
    a. An analytical balance with minimum precision to 0.5 mg,
    b. Large desiccating container that is air tight.
12. Use only American Chemical Society Reagent grade organic solvent.
13. Use deionized, glass-distilled H_2O.
14. Evaporate a control blank of 100 ml of each solvent used in any part of the analysis in tared beaker at room termperature and pressure.
15. Use only glass wash bottles and glass containers for all procedures that involve analytical workup. Only silica gel may be stored in plastic containers.
16. Organic-inorganic extraction of the impinger may be useful in determining emissions from some sources. Use the flowchart as a guide to this procedure.


Impinger H_2O
Record total volume
Add to 500 ml separatory funnel
Add 50 ml anhydrous diethyl ether Et_2O
Shake 3 minutes venting ether fumes periodically
Let stand for separation of layers
H_2O bottom layer separated
Et_2O to tared beaker
Extract H_2O twice again for a total of three Et_2O extractions. Combine extracts.
H_2O is then extracted three times with 50 ml chloroform ($CHCl_3$)
H_2O to tared beaker
$CHCl_3$ + Et_2O extracts
Evaporate H_2O at room temperature and pressure
Evaporate at room temperature and pressure

17. Procedures given here are only for cleaning Method 5 Train, although, they are good general starting point procedures for cleaning any sampling train.

The most important aspect of cleaning and analyzing the Method 5 Sampling Train is the practice of good laboratory technique. The sampling team may not include an experienced chemist; therefore, good technique may have to be learned by all team members. If an experienced analytical chemist is a member of the sampling team it would probably be best to allow him to assist in cleaning the equipment. This would help to assure good techniques and perhaps save time in preparing samples for more extensive qualitative or quantitative analysis.

SAFETY ON SITE

Source sampling is performed at a variety of industrial sites and under many different conditions. Adequate safety procedures may be different for any given situation; however, generally accepted industrial safety procedures should be helpful to source samplers. The test team must be aware of safe operating methods so that alert discretion may be used for team safety at a particular sampling site. Safety is an attitude that must be instilled in all sample team members. Well thought out and followed procedures will ensure the safety of all team members. The team concept essential to successful testing is vital for *safe* testing. It must be stressed that safety is everyone's responsibility for themselves as well as for other team members.

Key Factors to Good Safety

Knowledge and experience are the major factors in formulating sound safety practice. An individual must draw upon these factors in determining safe methods. A knowledge of standard safety and operating procedures will permit their application in any situation. This basic knowledge in conjunction with understanding of the job tasks and possible dangers assists in planning preventive safety measures. Plans for operating at the job site may be developed around these procedures. If an accident does occur, the people involved must be informed of proper emergency practices and use of first aid. Job experience and analysis of past accidents should be used in developing preventive safety programs.

Accident Analysis

The basic philosophy of a safety program should be that accidents are caused and, therefore, can be avoided or prevented. Accident analysis is a productive tool of this philosophy when it is used as a preventive step. This implies advance examination of a potentially hazardous situation to predict possible accidents and eliminate their causes. Accident analysis is most effective when employed after an accident has taken place. The analysis procedure involves listing the major and contributing causes of the accident. If the real causes of the accident are analyzed in this manner, corrective action will suggest itself. Accident analysis should include preventive suggestions from people involved at the job site or those who have been previously injured.

Common Causes of Accidents

There are a number of items that may be considered common causes of accidents:

1. Failure of supervisory personnel to give adequate instructions or inspections. This includes instructions for performing the job and safety requirements. Inspection of the job site is advisable for all applicable concerns and safety before, during, and after the job.
2. Failure of person in charge to properly plan or conduct the activity. Experiment design and performance are important factors in success and safety of a stack test. This includes providing adequate manpower for the task.
3. Improper design, construction, or layout. Design aspects relate to equipment used and plan of operation.
4. Protective devices or proper tools and equipment not provided. "Jerry rigging" and "making do" should only occur under unusual circumstances, not as standard practice.
5. Failure on the part of any personnel to follow rules or instructions. Safety is the responsiblity of each individual for himself and others around him. Personal disregard for safety rules jeopardizes the safety of all.

6. Neglect or improper use of protective devices, job equipment, or materials.
7. Faulty, improperly maintained devices. Poorly maintained job equipment is inexcusable.
8. Personnel without adequate knowledge or training for performing job tasks. All present should be capable of performing the job tasks assigned. Trainees should be closely supervised.
9. Personnel in poor physical condition or with a poor mental attitude for task. This can have implications for the attitude of personnel toward each other, the supervisor, the task itself, or working conditions.
10. Unpredictable agents outside the organization. This may mean contract personnel who do not abide by standard rules or something as unpredictable as a biting insect or bad weather.

Accident Prevention

Preventing accidents during a stack test begins with advance planning. Knowledge of process operations and important considerations of the site environment will give insight into chemical, mechanical, or electrical hazards that may be present. This knowledge will be useful in deciding on equipment to be used at the site. Knowledge of the weather conditions and logistical constraints further aid in establishing a safe test program. These items in conjunction with evaluation of site safety and first aid facilities will allow preparation of a source sampling experiment.

The source test program will operate at peak efficiency and safety if plans are properly followed. Thorough planning, including contingency actions, eliminates the confusion that often contributes to accidents. This planning must include allotment of sufficient time for completion of the task, taking into account possible delays. Test personnel should be well informed of the program procedures; their input for test performance and safety suggestions will be useful. Having once established an operating plan, all involved should adhere to it closely.

After thorough planning of the test program, attention focuses upon testing and safety equipment and on site operating practices. General comments on equipment preparation apply to both the sampling and safety apparatus. Experimental design and personnel suggestions should indicate what equipment will be needed on the site for all functions. Equipment should be prepared and assembled in advance; it should be checked for suitable operation or potential problems. Equipment that could handle unexpected situations should also be included. Carry only necessary equipment to the site and use it properly.

Work at the site must be organized following standard rules and work the plan carefully followed. Safety equipment should be used and personnel must remain alert to any changes on the site that could effect safe operation. All present should be made aware of any suspected problems.

Summary

The most important factor in any safety program is common sense. Common sense can, however, be an elusive element. Several steps presented in this section can help in developing sensible safety practices. Thorough advance planning and preparation for the jobs at hand begin the process of good safety practice. Informing involved personnel of all plans and using their suggestions about work safety increases the effectiveness of the planning. Analyzing a work situation for hazards, including past problems, into a coherent, organized safety program, usually results in common sense corrective procedures.

METHOD 5—SOURCE TEST DATA SHEETS

Preliminary Survey—Source Sampling Site

Date Survey investigator

Plant name City State

Previous test(s) by: Reports available

Plant contacts Title Phone

Title Phone

Title Phone

Complete directions to plant from point of origin

Local accommodations: nearest motel miles

Restaurants

Nearest hospital Phone

Rental cars and vans available

Plant Operation and Process Description

Description of process

Description of control equipment

Schematic Drawing of Process Operation (Note location of sampling)

Sites and control equipment:

Sampling sites	Anticipated constituents of stack gas
1.	
2.	
3.	
4.	
5.	

Process fuel type(s) ____________ Feed rate ____________

Process raw material(s) ____________ Consumption rate(s) ____________

Process production rate(s) ____________

Samples to be taken of: ____________

Plant operation: Continuous ____________ Batch ____________

Shift changes and breaks ____________

Plant facilities: Entrance requirements ________ Food ________ Restrooms ________

First aid ________ Safety equipment ________ Compressed air source ________

Laboratory ____________ Equipment available ____________

Reagents ____________ Ice ____________

Sampling Site and Stack Information

Sampling site	Type Pollutant emissions	Duct dimensions	Duct construction material	No. of sample ports	Port dimension	Diameters straight run to ports	Duct gas temp. °F	Duct gas velocity ft./sec.	Average Δp in. H_2O in duct	% Δp in gas	Stack pressure in. Hg.

Sketch of duct to be sampled with port locations and all dimensions

Sketch of sampling site including all dimensions

Access to work area	Work area (locate electrical outlets)

Electrical outlets available ______________

1. Voltage ______________
2. Extension cords needed, ______________ft.
3. Adapters ______________

Recommended modifications to sampling site ______________

____

____

Sampling method suggested ______________

Equipment needed: Sample probe length ______________ Nozzles ______________

Glassware ______________ Sample case: Horizontal traverse ______________ Vertical ______________

No. of needed sample cases ______ Meter consoles ______ Probes ______ Filter assemblies ______

Special equipment: ______________

____

____

Reagents needed ______________

____

Safety at Site

Condition description	Sampling site(s) general	Ladders	Scaffolds	Platforms	Lighting	Ventilation	Chemical hazard protection	Warning system
Good								
Adequate								
Poor								
Intolerable								

Personnel Safety Equipment

Item	Safety glasses	Full face shields	Hard hats	Safety shoes	Safety belts	Hearing protection	Respiratory equipment			Fire extinguishers	Chemical protection garments	Heat protecting garments	Asbestos aprons, gloves
							Purifying type	Self contained	Air supplied				
Needed at site													
Available at plant													
Must be brought by sample team													

Description of additional safety equipment recommended:

Comments:

Method 1—Sample and Velocity Traverses for Stationary Sources Sample Site Selection and Minimum Number of Traverse Points

Plant ____________ Location ____________ Date ____________

Sampling location ____________

Sample team operator(s) ____________

Sketch of stack geometry (including distances from sample site to any disturbances)

Interior duct cross-section dimension ____________ ft

Sampling port diameter ____________ in.

Sampling port nipple length ____________ in.

Stack cross-sectional area ____________ ft^2

Sampling site: diameter downstream of disturbance ____________ Diameters upstream ____________

Minimum number of sampling points ____________ Individual point sample time ____________

Total test time ____________

Comments:

Sketch of Stack Cross-Section Showing Sample Ports and all Dimensions

Sample point number	Circular stack % diameter	Distance from sample port opening in.
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
11.		
12.		

Gas Velocity Traverse Data

Plant ______________________________ Date ______________________________
Plant location ______________________________
Sampling location ______________________________
Operator(s) ______________________________
Dry molecular weight of stack gas ______________ lb/mole. Moisture content ______________ $\% H_20$
Pitot tube C_p __________ Barometric pressure __________ Stack static pressure __________
Stack cross-sectional area (A_s) ______________________ ft^2

Sample point no.	Distance into stack from stack wall	Port A			Port B			Port C			Port D		
		Δp H_20 in.	$\sqrt{\Delta p}$	T_s °F	Δp H_20 in.	$\sqrt{\Delta p}$	T_s °F	Δp H_20 in.	$\sqrt{\Delta p}$	T_s °F	Δp H_20 in.	$\sqrt{\Delta p}$	T_s °F
1													
2													
3													
4													
5													
6													
7													
8													
9													
10													
11													
12													

$$\text{Average } T_s\,°R\,(\overline{T}_s\,°R) = \left[\frac{\text{Sum of } T_s\,°F \text{ at each sample point}}{\text{Total no. sample points}}\right] + 460 = \_\_\_\_\_\_ °R$$

$$\text{Average } \Delta p\ (\overline{\Delta p}) = \left[\frac{\text{(Sum of the } \sqrt{\Delta p} \text{ at each sample point)}}{\text{Total no. sample points}}\right]^2 = \_\_\_\_\_\_ \text{ in. } H_20$$

$$\text{Average stack gas velocity } (\overline{v}_s) = K_p C_p \sqrt{\frac{\overline{T}_s}{P_s M_s}}\left(\sqrt{\Delta p}\right)_{av} = \_\_\_\_\_\_ \text{ ft /sec}$$

$$\text{where } K_p = 85.49 \text{ ft./sec.} \sqrt{\frac{\text{lb/lb mole (in. Hg)}}{(°R)\text{ (in. } H_2O\text{)}}}$$

Average actual stack gas volumetric flow rate

$$(\overline{Q}_a) = (\overline{v}_s)(A_s) \times 3600 \text{ sec /hr } = \_\_\_\_\_\_ \text{ ACFH}$$

Average dry stack gas volumetric flow rate at standard conditions

$$(Q_s) = (3600 \text{ sec /hr })(1 - B_{ws})(\overline{v}_s)(A_s)\ \frac{T_{std}}{P_{std}}\ \frac{P_s}{\overline{T}_s} = \_\_\_\_\_\_ \text{ DSCFH}$$

Orsat Field Data

Orsat identification no. ____________ Date reagents added ____________
Checked by ____________
Plant location ____________ Sampling date ____________
Operator(s) ____________
Sampling location ____________ Average fyrite CO_2 ____________
Moisture content of stack gas (B_{ws}) ____________ Fuel used ____________
Fuel feed rate ____________ Combustion source description ____________
Process production rate ____________ Steam production rate ____________
Comments: ____________

Test no.	Sample time		Analysis time	Burette readings		
	Start	Stop		CO_2	O_2	CO

Component	Mole fraction = %composition /100
CO_2	
$O_2 - CO_2$	
$CO - O_2$	
$100 - CO = N_2$	

Dry molecular weight of stack gas $(M_d) = \Sigma M_x B_x$

$$M_d = .44\,(\_\_\%CO_2) + .32\,(\_\_\%O_2) + .28\,(\_\_\%CO) + .28\,(\_\_\%N_2) = \_\_\ \text{g/g-mole}$$

Wet molecular weight of stack gas $(M_s) = M_d(1 - B_{ws}) + 18\text{gm/m}(B_{ws})$

$$M_s = (\_\_\ \text{g/g-mole}\ (1 - \_\_) + 18\ \text{g/g-mole}\ (\_\_) = \_\_\ \text{g/g-mole}$$

$$\%\ \text{Excess air in the duct}\ (\%EA) = \left[\frac{\%O_2 - 0.5(\%CO)}{(0.264)(\%N_2) - (\%O_2) + 0.5(\%CO)}\right] \times 100$$

$$\%\ EA = \left[\frac{(\_\_\%O_2) - 0.5(\_\_\%CO)}{(0.264)(\_\_\%N_2) - (\_\_\%O_2) + 0.5(\_\_\%CO)}\right] \times 100 = \_\_\_\%$$

Method 4—Reference Method for Determining Moisture Content of a Stack Gas

Date ______________________________

Plant ______________________________

Location ______________________________

Sampling location ______________________________

Operator ______________________________

Run no. ______________________________

Ambient temperature ______________________________

Barometric pressure ______________________________

Probe length ______________________________

Schematic of Stack Cross-Section

Traverse point #	Sample $0 + n \gtrless$.	Velocity head = Δp in. H_20	Rota-meter setting	Dry gas meter reading	Average inlet-outlet gas sample temp. at DGM	Gas temp. at last impinger

Sample Train No. ________

	Impinger Volume (WC) ml	Silica Gel (SG) gm (1 gm H_20 = 1 ml H_20)
Final		
Initial		
Diff.		

Standard ft^3 H_20 collected in the impinger =

$$V_{wc(std)} = WC_{H_20\,ml} \times 0.04707 \left(ft^3/ml\right) = \_\_ ft^3$$

Standard ft^3 H_20 collected in silica gel =

$$V_{wsg(std)} = SG_{H_20\,ml} \times 0.04715 \left(ft^3/g\right) = \_\_ ft^3$$

Volume metered at standard conditions =

$$V_{m(std)} = V_m \left(17.64\right) \frac{P_m}{T_m} = \_\_ ft^3$$

$$B_{ws} = \frac{V_{wc(std)} + V_{wsg(std)}}{V_{wc(std)} + V_{wsg(std)} + V_{m(std)}}$$

$$\%H_2O = B_{ws} \times 100 = \_\_\_\_$$

Particulate Field Data

Very Important—Fill in all Blanks

Plant ____________________
Run no. ____________________
Location ____________________
Date ____________________
Operator ____________________
Sample box no. ____________________
Meter box no. ____________________
Nomograph ID no. ____________________
Orsat no. ____ Date rebuilt ____
Fyrite no. ____ Date rebuilt ____

C_p ____________________
$\Delta H_@$ ____________________
P_m, in. Hg ____________________
P_s, in. Hg ____________________
B_{ws} (assumed) ____________________
M_d ____________________
M_s ____________________
T_m, °R ____________________
T_s, °R ____________________
$\Delta p_{avg.}$, in. H_20 ____________________

Test start time ____________________
Stop time ____________________
D_n calculated (in.) ____________________
D_n, used (in.) ____________________
Ambient temp., °F ____________________
Bar. pressure, in. Hg ____________________
Heater box setting, °F ____________________
Probe heater setting, °F ____________________
Average ΔH ____________________
Leak rate@15 in. Hg Pre-test ______ Post-test ______

Point	Clock time (min)	Dry gas meter CF	Pitot in H_2O Δp	Orifice ΔH in H_2O		Dry gas temp. °F		Pump vacuum in. Hg gauge	Box temp. °F	Impinger temp. °F	Stack press. in. Hg	Stack temp. °F	Fyrite %CO_2
				Desired	Actual	Inlet	Outlet						

Comments: ____
____

Test observers: ______________________________ ______________________________

continued

Point	Clock time (min)	Dry gas meter CF	Pitot in H_2O Δp	Orifice ΔH in H_2O		Dry gas temp. °F		Pump vacuum in. Hg gauge	Box temp. °F	Impinger temp. °F	Stack press. in. Hg	Stack temp. °F	Fyrite %CO_2
				Desired	Actual	Inlet	Outlet						

Comments: ____

____

Test observers: ____________________ ____________________

continued

Laboratory Analysis Data Particulate Source Sample

Analysis date(s) ____________ Analytical chemist ____________
Plant sampled ____________ Location ____________
Sampling location ____________ Sampling date(s) ____________
Sample run no. ____________ Sampling case no. ____________
Sample labels: H_2O ________ Silica gel ________ Filter ________ Probe ________
Impinger rinse ________ Dry particulate ________ Other ________
Analysis performed ____________
Reference method ____________ Analytical sample temp. ____________ °F
Comments: ____________
____
____

Moisture Data

Final volume H_2O in impingers ________ ml
Initial volume H_2O in impingers ________ ml
Volume H_2O condensed ________ ml

Final weight silica gel ________ gm
Initial weight silica gel ________ gm

Total Moisture

H_2O Condensed ________ ml

H_2O Absorbed ________ ml

H_2O Total ________ ml

Particulate Data

CH_3-CH_2-O-CH_2-CH_3/$CHCL_3$ extract
Flask no. ________
Final weight ________ mg
Initial weight ________ mg
Organic fraction ________ mg

Total Particulate Sampled

Organic fraction ________ mg
Inorganic fraction ________ mg
Front half particulates ________ mg

Extracted H_2O Flask No. ________
Final weight ________ mg
Initial weight ________ mg
Inorganic fraction ________ mg

Filter Flask No. ________
Final weight ________ mg
Initial weight ________ mg
Filter and particulates ________ mg
Filter no. ____ Tare weight ____ mg
Particulates ________ mg
Dry particulates and probe ________ mg
Front half particulates ________ mg

Total Particulates

Run No. ________

________ mg

Chapter 6

Source Sampling Calculations

This section presents the equations used for source sampling calculations. These equations are divided into two parts—equipment calibration, and source test calculations. Gaseous source test equations are included to aid the source sampler performing both particulate and gaseous emissions tests. The purpose of the section is to give the reader a quick reference to necessary mathematical expressions used in source testing experiments.

EQUIPMENT CALIBRATION EQUATIONS

Stausscheibe (Type S) Pitot Tube Calibration

Calibration Coefficient (C_p)

(Eq. 6-1) $$C_{p(s)} = C_{p(std)} \sqrt{\frac{\Delta p_{std}}{\Delta p_s}}$$

Deviation from Average C_p (Leg A or B of Type S tube)

(Eq. 6-2) $$Deviation = C_{p(std)} - C_p$$

Average deviation from the mean δ (Leg A or B)

(Eq. 6-3) $$\delta = \sum_{1}^{3} \frac{|C_{p(s)} - \bar{C}_{p(A\ or\ B)}|}{3}$$

Sampling Probe Calibration Developed by Experiment and Graphed for Each Probe Length

Test Meter Calibration Using Spirometer

Spirometer volume (temperature and pressure correction not necessary for ambient conditions)

(Eq. 6-4) $$[Spirometer\ displacement\ (cm)] \times [liters/cm] = liters\ volume$$

Convert liters to cubic feet (ft^3)

Test Meter Correction Factor

(Eq. 6-5) $$\frac{Spirometer\ Standard\ ft^3}{Test\ meter\ ft^3} = Test\ meter\ correction\ factor$$

Correct Volume

(Eq. 6-6) [*Test meter volume*] × [*Test meter correction factor*] = *correct volume*

Orifice Meter Calibration Using Test Meter

Test meter volumetric flowrate (Q_m) in cubic feet per minute

(Eq. 6-7) $Q_m = [\text{Test meter } (V_f) - \text{Test Meter } V_i] \times [\text{Test meter correction factor}]$

Proportionality Factor (K_m)

(Eq. 6-8)

$$K_m = Q_m \sqrt{\frac{P_m\ M_m}{T_m\ \Delta H}}$$

Orifice meter $\Delta H_@$ *Flow Rate*

(Eq. 6-9) 1. *English units* $\Delta H_@ = \dfrac{0.9244}{{K_m}^2}$

where $\Delta H_@ = 0.75$ *cfm at* 68°F *and* 29.92 *in. Hg*

(Eq. 6-9) 2. *Metric units* $\Delta H_@ = \dfrac{0.3306}{{K_m}^2}$

where $\Delta H_@ = 0.021\ m^3/min$ *at* 760 *mm Hg and* 20°C

Sampling Meter Console Calibration

Ratio of the accuracy of Console Gas Meter Calibration Test Meter (γ). Tolerance 1 ± 0.02

(Eq. 6-10)

$$\gamma = \frac{V_T\ T_m\ P_b}{V_m\ T_t\ \left(P_b + \dfrac{\Delta H}{13.6}\right)}$$

Meter Console Orifice Meter Calibration ($\Delta H_@$)

(Eq. 6-11) 1. $\Delta H_@ = \dfrac{K\ \Delta H}{P_b\ T_m} \left[\dfrac{T_T\theta}{V_T}\right]^2$

where $K = 0.0317$ *English units*
$= 0.0012$ *metric units*

(Eq. 6-12) 2. $\Delta H_@ = \dfrac{0.9244}{{\bar{K}_m}^2}$

Source Sampling Nomograph Calibration

Isokinetic ΔH Equation

(Eq. 6-13) Isokinetic

$$\Delta H = \left[846.72\, D_n^4\, \Delta H@\, C_p^2\, (1 - B_{ws})^2\, \frac{M_d\, T_m\, P_s}{M_s\, T_s\, P_m} \right] \Delta p$$

Sampling Nozzle Equation

(Eq. 6-14)

$$D_n = \sqrt{\frac{0.0358\, Q_m\, P_m}{T_m\, C_p (1 - B_{ws})} \sqrt{\frac{T_s\, M_s}{P_s\, (\overline{\Delta p})}}}$$

Adjusted C-Factor (C_p)

(Eq. 6-15)

$$C\text{-}factor\ adjusted = C_{factor} \left[\frac{Cp}{0.85} \right]^2$$

Adjusted C-Factor ($M_d \neq 29$)

(Eq. 6-15)

$$C\text{-}factor\ adjusted = C_{factor} \frac{1 - B_{ws} + 18\, B_{ws}/29}{1 - B_{ws} + 18 B_{ws}/M_d}$$

SOURCE SAMPLING CALCULATIONS

Method 1—Site Selection

Equal Area Equation (circular ducts)

(Eq. 6-16)

$$P = 50 \left[1 - \sqrt{\frac{2j - 1}{2n}} \right]$$

Equivalent Diameter for a Rectangular Duct

(Eq. 6-17)

$$D_E = \frac{2(length)\ (width)}{length + width}$$

Method 2—Gas Velocity and Volumetric Flow Rate

Average Stack Gas Velocity

(Eq. 6-18)

$$\bar{v_s} = K_p C_p \sqrt{\frac{T_s}{P_s M_s}} \left(\sqrt{\Delta p} \right)_{ave}$$

Average Dry Stack Gas Volumetric Flow Rate at Standard Conditions ($\bar{Q_s}$)

(Eq. 6-19)

$$\bar{Q_s} = 3600\ (1 - B_{ws}) \bar{v_s}\, A_s \left[\frac{T_{std}}{P_{std}} \right] \frac{P_s}{T_s}$$

Method 3—Orsat Analysis

Stack Gas Dry Molecular Weight

(Eq. 6-20) $M_d = \Sigma M_x B_x = 0.44(\%CO_2) + 0.32(\%O_2) + 0.28(\%N_2 + \%CO)$

Stack Gas Wet Molecular Weight

(Eq. 6-21)

$$M_s = M_d(1 - B_{ws}) + 18\ B_{ws}$$

Percent Excess Air (%EA)

(Eq. 6-22)

$$\%EA = \frac{(\%O_2) - 0.05(\%CO)}{0.264\ (\%N_2) - (\%O_2) + 0.5(\%CO)} \times 100$$

Method 4—Reference Moisture Content of a Stack Gas

Volume Water Vapor Condensed at Standard Conditions (V_{wc})

(Eq. 6-23)

$$V_{wc} = \frac{(ml\ H_2O)\varrho_w\ R\ T_{std}}{P_{std}\ M_w} = K_1\ (V_f - V_i)$$

where

$$\begin{aligned} K_1 &= 0.001333\ m^3/ml \text{ for metric units} \\ &= 0.04707\ ft.^3/ml \text{ for English units} \end{aligned}$$

Silica Gel

(Eq. 6-24)

$$K_2 = (W_f - W_i) = V_{w_{SG}}$$

where

$$\begin{aligned} K_2 &= 0.001335\ m^3/gm \text{ for metric units} \\ &= 0.04715\ ft.^3/gm \text{ for English units} \end{aligned}$$

Gas Volume at Standard Conditions

(Eq. 6-25)

$$V_{m(std)} = V_m Y_m \left(\frac{T_{std}}{P_{std}}\right) \left(\frac{P_b + \frac{\Delta H}{13.6}}{T_m}\right)$$

Moisture Content

(Eq. 6-26)

$$B_{ws} = \frac{V_{wc} + V_{w_{SG}}}{V_{wc} + V_{w_{SG}} + V_{m(std)}}$$

Method 5—Particulate Emissions Testing

Dry Gas Volume Metered at Standard Conditions

Leak Rate Adjustment

(Eq. 6-27)

$$V_m = [V_m - (L_1 - L_a)\theta - \sum_{i=2}^{N} (L_i - L_a)\theta_i - (L_p - L_a)\theta_p]$$

Standard Dry Volume at Sampling Meter

(Eq. 6-28)

$$V_{m(std)} = V_m Y_m \left(\frac{T_{std}}{P_{std}}\right) \left(\frac{P_b + \frac{\Delta H}{13.6}}{T_m}\right)$$

Isokinetic Variation

Raw Data

(Eq. 6-29)

$$\%I = \frac{100\ T_s\ [K_3 V_{lc} + (V_m/T_m)\ (P_b + \Delta H/13.6)]}{60\ \theta_s\ v_s P_s A_n}$$

where

$$K_3 = 0.003454\ \frac{mm\ Hg\ m^3}{ml\ ^\circ K}$$

$$= 0.002669\ \frac{in.\ Hg\ ft^3}{ml\ ^\circ R}$$

Note: This equation includes a correction for the pressure differential across the dry gas meter measured by the orifice meter—average sampling run ΔH readings.

Intermediate Data

(Eq. 6-30)

$$\%I = 100 \frac{T_s\ V_{m(std)}\ P_{std}}{T_{std}\ \bar{v}_s\ \theta\ \ A_n\ P_s\ 60(1\text{-}B_{ws})} = K_4\ \frac{T_s\ V_{m(std)}}{P_s\ \bar{v}_s\ A_n \theta (1 - B_{ws})}$$

where

$K_4 = 4.320$ *for metric units*
0.09450 *for English units*

Method 8 —Sulfuric Acid Mist and Sulfur Dioxide Emissions Testing

Dry volume metered at standard conditions (see equations in previous sections of this outline)

Sulfur Dioxide concentration

(Eq. 6-31)

$$c_{so_2} = K_3\ \frac{N(V_t - V_{tb})\left(\frac{V_{solution}}{V_{aliquot}}\right)}{V_{m(std)}}$$

where

$K_3 = 0.03203$ *g/meq for metric units*
$= 7.061 \times 10^{-5}$ *lb/meq for English units*

Sulfuric acid mist (including sulfur trioxide) concentration

(Eq. 6-32)

$$c_{H_2SO_4} = K_2 \frac{N(V_t - V_{tb})\left(\frac{V_{solution}}{V_{aliquot}}\right)}{V_{m(std)}}$$

where $K_2 = 0.04904\ g/meq$ for metric units

$= 1.08 \times 10^{-4}\ lb/meq$ for English units

Isokinetic Variation

Raw Data

(Eq. 6-33)
$$\%I = 100\ \frac{T_s\ [K_4 V_{lc} + (V_m/Tm)(P_b + \Delta H/13.6)]}{60\theta A_n v_s P_s}$$

where $K_4 = 0.003464\ mm\ Hg - m^3/ml - {}^\circ K$

$= 0.002676\ in.\ Hg - ft^3/ml - {}^\circ R$

Concentration Correction Equations

Concentration Correction to 12% CO_2

(Eq. 6-34)
$$c_{s12} = c_s \left[\frac{12}{\%CO_2}\right]$$

Concentration Correction to 50% Excess Air Concentration

(Eq. 6-35)
$$c_{s50} = \left[\frac{100 + \%EA}{150}\right]$$

Correction to 50% Excess Air Using Raw Orsat Data

(Eq. 6-36)
$$c_{s50} = \frac{c_s}{1 - \left[\frac{(1.5)(\%O_2) - (0.133)(\%N_2) - 0.75(\%CO)}{21}\right]}$$

F-Factor Equations

F_c Factor

(Eq. 6-37)
$$E = F_c\, c_s \left(\frac{100}{\%CO_2}\right)$$

Used when measuring c_s and CO_2 on a wet or dry basis.

F_d Factor

When measuring O_{2d} and c_s on a dry basis

(Eq. 6-38)
$$E = F_d\, c_{sd} \left[\frac{20.9}{20.9 - \%O_{2d}}\right]$$

When measuring O_{2d} and c_s on a wet basis

(Eq. 6-39)
$$E = F_d\, c_{ws} \left[\frac{20.9}{20.9(1 - B_{ws}) - \frac{\%O_{2w}}{1 - B_{ws}}}\right]$$

F_w Factor

- When measuring c_s and O_2 on a wet basis
- B_{wa} = moisture content of ambient air
- Cannot be used after a wet scrubber

(Eq. 6-40)

$$E = F_w\, c_{ws} \left[\frac{20.9}{20.9(1 - B_{wa}) - \%O_{2w}} \right]$$

F_o Factor

1. Miscellaneous factor for checking Orsat data

(Eq. 6-41)

$$F_o = \frac{20.9}{100}\,\frac{F_d}{F_c} = \frac{20.9 - O_{2d}}{\%CO_{2d}} \qquad \left(\begin{array}{c} O_2 \text{ and } CO_2 \text{ measured} \\ \text{on dry basis} \end{array} \right)$$

Opacity Equations

%Opacity

(Eq. 6-42)

$$\%\,Opacity = 100 - \%\ Transmittance$$

Optical Density

(Eq. 6-43)

$$Optical\ Density = \log_{10} \left[\frac{1}{1 - Opacity} \right]$$

(Eq. 6-44)

$$Optical\ Density = \log_{10} \left[\frac{1}{Transmittance} \right]$$

Transmittance

(Eq. 6-45)

$$Transmittance = e^{-naql}$$

Plume Opacity Correction

(Eq. 6-46)

$$\log(1 - O_1) = (L_1/L_2)\, \log(1 - O_2)$$

Chapter 7

Report Writing

The report of a source sampling test presents a record of the experimental procedure and the test results; it is a written statement describing a scientific experiment and should follow the basic rules of accepted form. The report must state the objectives of the experiment, the procedures used to accomplish these objectives, results of the experiment, and conclusions that may be drawn from these results. The information should be presented in a clear, concise manner. The report must document all aspects of the testing for it may be used in litigation. A suggested format for the report is given in this section with a brief explanation of each topic. An outline of the format follows these explanations.

PRESENTATION

The test report should be presented as a professional document. It should be bound in an appropriate cover and contain a cover page giving the title of the report, the identity of the organization for which the test was performed, and the test team as well as the location and dates of the testing. Following the cover page should be a signature page with a statement of the careful performance of the test and preparation of results signed by all test participants, laboratory personnel, and supervisors. This is essential for documentation and legal purposes. A table of contents then follows, and includes all topic listings and appendixes with page numbers. An accurate table of contents is always appreciated by those reading the report.

INTRODUCTION

The report introduction will briefly define the purpose of the test. It will include a short description of the basic sampling method and of the process and control devices used and give testing location and date along with the names of the test team personnel. The introduction should also identify industrial or regulatory agency personnel present on site during the tests.

SUMMARY OF RESULTS

The summary of test results is extremely important. This is usually the first item of the report read; often it is the only section that anyone reads and it is presented as the first item in the report for this reason. The summary of results is a concise statement of test methods and results. The sampling equipment is described as are the test methods employed. Standard methods are referenced to State or Federal guidelines, with approved method changes referenced to sources used or regulatory agency giving approval. The source emission rate determined by the test is expressed in appropriate English and metric units. Comments concerning the process rate and continuity during the test are also given. State and/or Federal regulatory emission rates are stated. The test summary should then give a conclusion about the test program and the results.

PROCESS DESCRIPTION

A full description of the process is essential. Include the process description with any charts of process monitoring equipment (fuel feed rate, steam flow, materials produced, etc.) and samples of calculations used for determining production rate. Provide a flow diagram of the entire process with all pertinent information regarding production and control equipment. A full accounting of process operating conditions during the test should be included with these charts and diagrams. Specific attention must be given to the control equipment. State the manufacturer's name and operating specification with notes on the operation of the device during the test.

TESTING METHODOLOGY

A detailed description of the sampling scheme is given in this section. Drawings, photographs, or blueprints of the stack or duct and sampling ports, including all dimensions actually taken by the test team, are required. These must be accompanied by a diagram showing the location of the sampling points within the duct and all important dimensions. Descriptions of the sampling and analytical procedures are required. The methods and specific equipment used should be stated and referenced. All modifications to standard procedures must be noted. Justification for these changes in addition to authorized approval from regulatory agencies or industrial personnel is necessary.

RESULTS

The results portion of the report should allow easy access and review of summarized data. Present raw field and laboratory data in summary charts and tables with easily understood examples of the calculations made. Listing the results of these calculations in easy-to-read tables increases the value of this section.

APPENDIX

The appendix should include the following items:

- Test Log—record of events at the site.
- Raw field data sheets (or signed copies).
- Laboratory report including raw data, tables, and calibration graphs.
- Testing equipment listing:
    1. Design and manufacture;
    2. Calibration procedures and data sheets;
    3. Serial numbers of equipment used in test.
- A copy of Federal Register or other reference procedure outline.
- A copy of applicable statutes and regulations concerning the testing.

QUICK REFERENCE OUTLINE FOR REPORT WRITING

- I. **Presentation of report**
  - A. Bind in suitable cover
  - B. Cover page
    - 1. Report title
    - 2. Organization requesting test
    - 3. Organization performing test
    - 4. Location and dates of test
  - C. Table of contents

- II. **Report**
  - A. Introduction
    - 1. Test objectives
    - 2. Brief process and control equipment description
    - 3. Test dates and personnel
      - a. Samplers
      - b. Observers
  - B. Summary of results
    - 1. Brief test method identification
    - 2. Regulatory agency approval of method
    - 3. Comments on process operation
    - 4. Emission rate determined by the test
    - 5. Emission rate limit given by law
  - C. Process description
    - 1. Describe process
    - 2. Describe control equipment
    - 3. Flow diagram of entire process
    - 4. Charts and calculations of process production rates
  - D. Testing methodology
    - 1. Sampling scheme with drawing and dimensions of site and sample points
    - 2. Description of sampling method
    - 3. Description of analytical method
    - 4. Modifications to methods and approved justification
  - E. Results
    - 1. Summary of data
    - 2. Charts and tables
    - 3. Example calculations
  - F. Appendix

Chapter 8

Error Analysis
Role of the Observer

ERROR ANALYSIS*

Introduction

The problem of accuracy in stack sampling measurements is considered and debated in almost every report or journal article in which stack sampling data appear. There exists, however, a great deal of misunderstanding in the engineering community on the difference between error, precision, and accuracy. This misunderstanding often leads to a misinterpretation of analytical studies of stack sampling methods. The type of error analysis often used applies only to "randomly distributed error with a normal distribution about the true value."

A discussion of the definitions of terms normally used in error analysis will be given in a course lecture. The definitions are also included in this manual for your future reference. It is hoped that by studying this section the student will realize the limitations of error analysis procedures and will be able to more carefully design experiments that will yield results close to the "true" value.

Definitions

Error: This word is used correctly with two different meanings (and frequently incorrectly to denote what properly should be called a "discrepancy"):

(1) To denote the difference between a measured value and the "true" one. Except in a few trivial cases (such as the experimental determination of the ratio of the circumference to the diameter of a circle), the "true" value is unknown and the magnitude of the error is hypothetical. Nevertheless, this is a useful concept for the purpose of discussion.

(2) When a number such as $\sigma = \pm 0.000008 \times 10^{10}$ is given or implied, "error" refers to the estimated uncertainty in an experiment and is expressed in terms of such quantities as standard deviation, average deviation, probable error, or precision index.

Discrepancy: This is the difference between two measured values of a quantity, such as the difference between those obtained by two students, or the difference between the value found by a student and the one given in a handbook or textbook. The word "error" is often used incorrectly to refer to such differences

Many beginning students suffer from the false impression that values found in handbooks or textbooks are "exact" or "true." All such values are the results of experiments and contain uncertainties. Furthermore, in experiments such as the determination of properties of individual samples of matter, handbook values may actually be less reliable than the student's because the student's samples may differ in constitution from the materials which were the basis of the handbook values.

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*Adapted from Y. Beers, *Theory of Errors*, Addison-Wesley, Reading, Mass, (1958) pp.1-6.

Random Errors: Sometimes when a given measurement is repeated the resulting values do not agree exactly. The causes of the disagreement between the individual values must also be causes of their differing from the "true" value. Errors resulting from these causes are called random errors. They are also sometimes called experimental or accidental errors.

Systematic or Constant Errors: If, on the other hand, all of the individual values are in error by the same amount, the errors are called systematic or constant errors. For example, all the measurements made with a steel tape that includes a kink will appear to be too small by an amount equal to the loss in length resulting from the kink.

In most experiments, both random and systematic errors are present. Sometimes both may arise from the same source.

Determinate and Indeterminate Errors: Errors which may be evaluated by some logical procedure, either theoretical or experimental, are called determinate, while others are called indeterminate.

Random errors are determinate because they may be evaluated by application of a theory that will be developed later. In some cases random or systematic errors may be evaluated by subsidiary experiments. In other cases it may be inherently impossible to evaluate systematic errors, and their presence may be inferred only indirectly by comparison with other measurements of the same quantity employing radically different methods. Systematic errors may sometimes be evaluated by calibration of the instruments against standards, and in these cases whether the errors are determinate or indeterminate depends upon the availability of the standards.

Corrections: Determinate systematic errors and some determinate random errors may be removed by application of suitable corrections. For example, the measurements that were in error due to a kink in a steel tape may be eliminated by comparing the tape with a standard and subtracting the difference from all the measured values. Some of the random error of this tape may be due to expansion and contraction of the tape with fluctuations of temperature. By noting the temperature at the time of each measurement and ascertaining the coefficient of linear expansion of the tape, the individual values may be compensated for this effect.

Precision: If an experiment has small random errors, it is said to have high precision.

Accuracy: If an experiment has small systematic errors, it is said to have high accuracy.

Adjustment of Data: This is the process of determining the "best" or what is generally called the most probable value from the data. If the length of a table is measured a number of times by the same method, by taking the average of the measurements we can obtain a value more precise than any of the individual ones. If some of the individual values are more precise than others, then a weighted average should be computed. These are examples of adjustment of data for directly measured quantities. For computer quantities the process may be specialized and complicated.

Classification of Errors

Systematic Errors:

(1) Errors of calibration of instruments.

(2) Personal errors. These are errors caused by habits of individual observers. For example, an observer may always introduce an error by consistently holding his head too far to the left while reading a needle and scale having parallax.

(3) Experimental conditions. If an instrument is used under constant experimental conditions (such as of pressure or temperature) different from those for which it was calibrated, and if no correction is made, a systematic error results.

(4) Imperfect technique. The measurement of viscosity by Poiseuille's Law requires the measurement of the amount of liquid emerging from an apparatus in a given time. If a small amount of the liquid splashes out of the vessel which is used to catch it, a systematic error results.

Random Errors:

(1) Errors of judgment. Most instruments require an estimate of the fraction of the smallest division, and the observer's estimate may vary from time to time for a variety of reasons.

(2) Fluctuating conditions (such as temperature, pressure, line voltage).

(3) Small disturbances. Examples of these are mechanical vibrations or, in electrical instruments, the pickup of spurious signals from nearby rotating electrical machinery or other apparatus.

(4) Definition. Even if the measuring process were perfect, repeated measurements of the same quantity might still fail to agree because that quantity might not be precisely defined. For example, the "length" of a rectangular table is not an exact quantity. For a variety of reasons the edges are not smooth (at least if viewed under high magnification) nor are the edges accurately parallel. Thus even with a perfectly accurate device for measuring length, the value is found to vary depending upon just where on the cross section the "length" is measured.

Illegitimate Errors: These errors are almost always present, at least to a small degree, in the very best of experiments and they should be discussed in a written report. However, there are three types of avoidable errors which have no place in an experiment, and the trained reader of a report is justified in assuming that these are not present.

(1) Blunders. These are errors caused by outright mistakes in reading instruments, adjusting the conditions of the experiment, or performing calculations. These may be largely eliminated by care and by repetition of the experiment and calculations.

(2) Errors of computation. The mathematical machinery selected for calculating the results of an experiment (such as slide rules, logarithm tables, adding machines) should have errors small enough to be completely negligible in comparison with the natural errors of the experiment. Thus if the data are

accurate to five significant figures, it is highly improper to use a slide rule capable of being read to only three figures, and then to state in the report that "slide rule error" is a source of error. Such a slide rule should be used for calculating the results of an experiment having only three or preferably two significant figures. On the other hand, if the experiment does give five significant figures, five or six-place logarithm tables or some other more accurate means of calculation should be used.

(3) Chaotic Errors. If the effects of disturbances become unreasonably large—that is, large compared with the natural random errors—they are called chaotic errors. In such situations the experiment should be discontinued until the source of the disturbance is removed.

THE ROLE OF THE AGENCY OBSERVER*

Introduction

Air pollution control agency personnel who may not be directly involved in the compliance source sampling process are often called upon to evaluate source tests performed by environmental consultants or companies. Since emission testing requires that industry, at their own expense, contact highly skilled source test teams, the source test observer should be prepared to ensure that proper procedures are followed and that representative data is obtained.

The main purpose for the agency's observation of the compliance test is to determine that the test data is representative. There are other valid reasons to observe the test, such as establishing baseline conditions for future inspections, but the major emphasis is on the evaluation of the acceptability of the initial compliance test.

The seven steps an agency generally uses for establishing the compliance of a source with the agency's regulatory requirements are as follows:

1. Familiarize—the agency establishes contact with the source and becomes familiar with operations, emissions, and applicable regulations.
2. Schedule source test—this may be part of a compliance schedule of Federal Standard of Performance for Stationary Source Enforcement (NSPS).
3. Establish methodology—testing requirements should be established and a testing plan developed by the agency.
4. Final plan and test procedure develoment—a presurvey should be conducted by a member of the testing team. A pretest meeting between the agency, source representative, and test team representative should be held to develop the final test plan.

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*Adapted from W. G. DeWees, *Supplemental Training Material for Technical Workshop on Evaluating Performance Tests*, DSSE, EPA. PEDCo—Environmental Specialists

5. Actual compliance tests – observation of the facility operations and testing methodology.
6. Review of test data – determination of compliance and official notification.
7. Continuing enforcement of compliance – followup inspections using data generated from source tests as baseline for comparison purposes.

There are five areas where problems might develop in obtaining a sample representative of the source emissions. If a question arises as to the integrity of any one of these areas, the compliance test may be considered nonrepresentative. These five areas are:

- The process and control equipment must be operated in such a manner as to produce representative atmospheric emissions.
- The sample port and point locations must be representative of the atmospheric emissions.
- The sample collected in the sample train must be representative of the sample points.
- The sample recovered and analyzed must be representative of the sample collected in the sample train.
- The reported sample results must be representative of the recovered and analyzed sample.

The source test to be monitored by the observer, then is developed and conducted by the source test team and observer in four major phases: (a) preparing and planning, (b) conducting the test, (c) recovering, transporting, and analyzing the sample, and (d) submitting the report. Discussion of these phases follows.

Preparing and Planning—In the initial phase of preparation and planning, the agency must clarify for the source test team leader and process representative all the procedures and methods to be used during the entire testing program.

The review of the compliance test protocol submitted by the plant management or test consultant will explain the intended sampling plan to the observer. Two of the more important items to be checked are any deviations from standard sampling procedures and the proposed operation of the facility during the compliance test.

Many types of processes, sampling locations, and pollutants require some modification to the standard sampling procedure. The agency must determine if the modification will give equivalent and/or greater measurement results than would be obtained with the standard method.

The other major determination to be made from the test protocol is defining what constitutes normal operation of the facility. Example checklists for power plants and electrostatic precipitators are presented.

The plant representative should understand and agree to all facility baseline conditions prior to the compliance testing, since the determination of representative operation of the facility is for the protection of both the regulatory agency and the plant. The plant representative may suggest additional factors that could be considered as an upset condition and which would not produce representative emissions.

Example checklists for power plants.

8.1 FOSSIL FUEL FIRED INDIRECT HEAT EXCHANGE

Checklist for process monitor

Monitor name ____________ Test date ____________

Facility representative ____________________

Company name ____________________

Designation of facility ____________________

Designation of unit being tested ____________________

Maximum heat input ____________ million Kcal/hour

____________ million Btu/hour

Boiler nameplate capacity ____________, pounds steam/hr

Electric generator capacity ____________ megawatts

Induced draft fan capacity ____________ CFM

at ____________ in. H_2O and ____________ °F.

Motor drive ________hp.; amps ________; volts ________

Combustion control Automatic Hand

Type of soot blowing Continuous Period

Control of soot blowing

Automatic sequential

Hand

____________time cycle

Describe the a.p.c. system ____________________

8.2 MONITORING FUEL DURING TEST

Note fuel feed measuring devices may be some distance from other instrumentation to be monitored.

Coal (classified by ASTMD 388-66)

Bituminous Sub-bituminous Anthracite Lignite

Coal feel measured by

Automatic conveyor scale

Batch weighing—dumping hoppers

Other (describe) ____________________

None

Liquid fossil fuel

Crude Residual Distillate

Liquid fuel feed measured by

Volumetric flow meter, make ________ model ________

Other (describe) ____________________

None

Gaseous fossil fuel

Natural gas Propane Butane

Other

Gaseous fuel feed measured by

Volumetric flow meter, make ________ model ________

Other (describe) ____________________

Other fuel (describe) ____________________

Other fuel feed measured by ____________________

____

8.3 FUEL INPUT DATA

Automatic weighing or metering

	Counter (totalizer) reading			
	Time	Coal	Oil	Gas
End test	____	____	____	____
Begin test	____	____	____	____
Difference				
Units fed during test	____	____	____	____
Counter conversion factor	____	____	____	____
Fuel per counter unit	____ tons	____ gal.	____ cu. ft.	
Fuel fed during test	____ tons	____ gal.	____ cu. ft.	
Fuel sampled during test				
Number of samples	____	____	____	
Total quantity of sample	____	____	____	
Date of last calibration of automatic metering device	____	____	____	

For manual weighing or other:

Use this space for monitoring procedure and calculations

____

____

8.4 FUEL ANALYSIS

Proximate analysis—as fired solid and liquid fuels

Component	% by weight Typical	This test
Moisture		
Ash		
Volatile matter		
Fixed carbon		
Sulfur		
Heat value, Btu/lb		

or ultimate analysis—which includes the proximate analysis plus the following

Nitrogen ____________________

Oxygen ____________________

Hydrogen ____________________

8.5 MONITORING BTU INPUT BY HEAT RATE OF BOILER-GENERATOR UNIT AND Kw-hr OUTPUT METER WHEN APPLICABLE

Purpose is to serve as a **check** on other calculation procedures. Boiler generator heat rate ________________Btu/kw-hr. Heat rate is obtained from facility representative. The heat rate curve is more accurate if corrections for super heat temperature, reheat temperature and condenser back pressure are applied for the test load condition.

Record data from generator output meter

	Time	**Meter reading Kw-hr Output**
End test	______	____________
Begin test	______	____________
Difference		
Kw-hrs. generated during test		____________

Btu input during test =

Kw-hrs. generated X heat rate (Btu/Kw-hr.)

Btu input during test =

____________ × ____________ = Btu

8.6 MONITORING STEAM GENERATOR OUTPUT BY STEAM FLOW METER

(Usually combined with air flow)

Steam flow measured by

Integrator on steam flow meter

Integrating chart from recorder

Calibration date ______________________

Primary purpose of steam flow monitoring is to indicate the load on the boiler during the test to observe and communicate to test team leader sudden significant change in steam flow which would be accompanied by significant changes in gas flow. Steam flow and flue gas flow changes parallel each other closely.

Record data by integrator on steam flow meter

	Time	**Integrator**	**Reading**
End test	________	________	________
Begin test	________	________	________
Difference			

Alternate factor ________________

Total steam flow during test ________________ pounds

Steam chart

Mark beginning and end of test runs on the steam chart and request a copy.

Chart marked and copy received.

8.7 OTHER INSTRUMENTAL DATA

Exhaust gas temperature just before the a.p.c. device

Max ________°F Min ________°F Avg ________°F

Draft	**Primary Collector**	**Secondary Collector**
Before control device	______in H_2O	______in H_2O
After control device	______in H_2O	______in H_2O

Combustion recorders (indicate those available)

CO_2 Opacity

O_2 NO_x

SO_2

Obtain copy of recorders available and mark beginning and ending time of test.

- **Soot blowing**

Was soot blowing to be included in the test period

No Yes

If yes, record time and duration of soot blowing. ____________

____

- **Special observations** of any unusual operating conditions

____

____

____

8.8 ELECTROSTATIC PRECIPITATOR—CHECKLIST FOR CONTROL DEVICE MONITOR

Parameters of design and operation affecting performance

Monitor name ______________ Test date ______________

Design efficiency ________________________

Rectifier power output	**Design**	**During test**
Voltage, kilowatts	________	________
Current, milliamps	________	________
Sparking rate, sparks/min	________	________
Gas volume, acfm	________	________
Gas velocity, fps	________	________
Gas temperature, °F	________	________
Fan motor, amperes	________	________
Electrical fields in direction of flow		________
Number of rappers in direction of flow		________

Other method of cleaning plates____________________

____

ESP rapping sequence

Normal ______________________________

____

During test ______________________________

____

Hopper ash removed sequence

Normal ______________________________

Notes of unusual conditions during test

____

____

____

8.9 SCRUBBER—CHECKLIST FOR CONTROL DEVICE MONITOR

Parameters of design and operation affecting performance

Monitor name ____________ Test date ____________
Type of scrubber
Venturi Plate Other ____________
Turbulent bed Spray
Design of efficiency ____________

	Design	During test
Pressure drop across scrubber, in H_2O	________	________
Nozzle pressure, pounds/sq in	________	________
Gas volume flow out of scrubber, cfm	________	________
Fan motor amperes	________	________
Liquid flow rate to scrubber gal/min	________	________
Liquid/gas rates, L/g	________	________
Recirculation of scrubbing liquid	________	________
Gas temperature of scrubber	________	________

Preconditioning or dilution air ____________

During test ____________

Rates of usual conditions during test ____________

8.10 FABRIC FILTER—CHECKLIST FOR CONTROL DEVICE MONITOR

Parameters of design and operation affecting performance

Monitor name ____________ Test date ____________

Pressure drop across	Design	During test
Collector in H_2O		
Just after bag cleaning	________	________
Just before bag cleaning	________	________
Gas volume to bag house, acfm	________	________
Fan motor amperes	________	________
Type of cleaning		
Shaking – number of compartments		________
Reverse air flow – number of compartments		________
Repressuring – number of compartments		________
Pulse jet (cleaned while on stream)		________

Other ____________
Cleaning cycle
Normal ____________

During tests ____________

Particulate removal sequence
Normal ____________

During test ____________

Notes of unusual conditions during test ____________

Preconditioning or dilution air ____________

8.11 CYCLONE/MULTICYCLONE—CHECKLIST FOR CONTROL DEVICE MONITOR

Parameters of design and operation affecting performance

Monitor name ____________ Test date ____________
Design efficiency ____________

	Design	During test
Pressure drop across		
Collector in H_2O	________	________
Gas volume, acfm	________	________
Gas temperature °F	________	________
Fan motor amperes	________	________

Is the collector sectionalized with dampers for control of
Δp No Yes
If yes, how were dampers positioned during test? ____________

Hopper ash removal sequence
Normal ____________

During test ____________

Notes of unusual conditions during test ____________

The observer must be familiar with the process to be sampled. Whenever possible, the agency field inspector should be the observer for the process and control equipment. If the process is large or complicated, the observer may be aided by a process control engineer from the agency. An emission test run at the wrong process rating or without sufficient process data will not constitute a valid test. Familiarity with the specific process can be acquired through one or more of the many inspection manuals prepared by the Environmental Protection Agency for this purpose. These manuals will indicate the methods and devices employed in monitoring process rates and/or weights.

Conducting the Test—Some compliance tests may be routine enough that a pretest meeting on the morning before sampling begins will be sufficient to provide a complete understanding between all parties involved.

The review of the team leader's test protocol should have initiated the formulation of the observer's sampling audit plan. The observer's audit plan should contain the tentative testing schedule, facility baseline conditions preparation or modification of observer's checklist, and details for handling irregular situations that could occur during emission testing.

The sample testing schedule should allow the observer to plan his duties in a logical order and should increase his efficiency in obtaining all of the required data.

The observer's testing forms normally should need little modification. Any accepted modification to the normal sampling procedure should be covered by additional checks from the observer.

The observer should be prepared to handle any nonroutine situations that could arise during sampling procedures. A list of potential problems and their solutions should be made before the actual testing. The list should include minimum sampling requirements and process operating rates. The observer should also know who in his organization is authorized to make decisions that are beyond his own capability or authority.

The number of agency personnel observing the performance test must be adequate to ensure that the facility operation (process and control equipment) is monitored and recorded as a basis for the present and future evaluations. The observing team should be able to obtain visible emission readings and transmissometer data for comparison with measured emission rates and should be able to ensure that the prescribed agency testing methodology was followed.

The plant representative should be available during testing to answer any questions that might arise about the process or to make needed process changes. It should be understood that, if any problems do arise, all three parties would be consulted. Since the observer may approve or disapprove the test, his intentions should be stated at the pretest meeting.

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Before actually proceeding with the test, the observor should check the calibration forms for the specific equipment to be used. As a minimum, these should include calibration of the:

- Pitot tube
- Nomograph (if used)
- Dry Gas Meter
- Orifice Meter

If there is any question as to whether proper calibration procedures were followed, the problem should be resolved before initiating the test.

During the test, the outward behavior of the observer is of utmost importance. He should perform his duties quietly, thoroughly, and with as little interference and conversation with the source test team as possible. He should deal solely with the test supervisor and plant representative or have a clear understanding with them should it become necessary to communicate with the source test technicians or plant operators. Conversely, he should exercise caution in answering queries from the source test team technicians and plant operators directly and refer such inquiries to their supervisor. He should, however, ensure that sampling guidelines are adhered to and inform the test team if errors are being made.

Several checks must be made by the observer to ensure adherence to the proper sampling procedures. To eliminate the possibility of overlooking a necessary check, an observer's checklist should be used for the sampling procedures and facility operation. An example of one of these checklists is included.

To understand the relative importance of the measurement of parameters of emission testing, the observer should know the significance of errors. A discussion of errors is given in a preceding section of this chapter.

Generally, it is best to have two agency observers at the source test. If only one observer is present, however, the following schedule given should be followed.

For the first Method 5 run, when the facility is operating in the correct manner, the observer should go to the sampling site and observe the sample train configuration and the recording of the initial data. The observer should oversee the initial leak check (and the final post test leak check). When the observer is satisfied with the sample train preparation, the test may be started. The sampling at the first port and the change-over to the second port should be observed. If satisfied with the tester's performance, the observer should go to a suitable point from the stack and read visible emissions for a 6 minute period.

The facility operations must then be checked. This includes data from fuel flow meters, operating monitors, fuel composition, F factors, etc. Also check data from continuous emissions monitoring equipment such as opacity monitors and SO_2 analyzers. This data will be useful in evaluating the Method 5 data. If the process and control equipment have operated satisfactorily and the data has been recorded as specified, the observer should make another visible emission reading for 6 minutes, then return to the sample site to observe the completion of the test. The final readings and the leak check after the completion of the test are two of the more important items to be checked. The transport of the sample train to the cleanup area and the sample recovery should then be observed.

Sampling checklists.

8.12 GENERAL/SAMPLING SITE

Stack/duct cross section dimensions ________
equivalent diameter ____________
Material of construction _____ corroded? _____ leaks? _____
Internal appearance: corroded? __________
caked particulate? ________ thickness ________
Insulation? ____ thickness ____ lining? ____ thickness ____
Nipple? ____ I.D. ____ length ____ flush with inside wall? ____
Straight run before ports ______ diameters ______
Straight run after ports ______ diameters ______
Photos taken? __________ of what __________

Drawing of sampling location:

Minimum information on drawing: stack/duct dimensions, location and description of major disturbances and all minor disturbances (dampers, transmissometers, etc.). and cross sectional view showing dimensions and port locations.

8.13 RUN ASSEMBLY/FINAL PREPARATIONS

(Use one sheet per run if necessary) Run # ______

Filter holder clean before test? ______
Filter holder assembled correctly? ________
Probe liner clean before test? _____ nozzle clean? _____
nozzle undamaged? ____________
Impingers clean before test? ________
impingers charged correctly? Yes
Ball joints or screw joints? __ grease used? __ kind of grease __
Pitot tube tip undamaged? ________
pitot lines checked for leaks? ______ plugging? ______
Meter box leveled? ____ pitot manometer zeroed? ____
orifice manometer zeroed? _____
Probe markings correct? ____ probe hot along entire length? ____
Filter compartment hot? __ temperature information available? __
Impingers iced down? ____ thermometer reading properly? yes
Barometric pressure measured? __ if not, what is source of data __
$\Delta H_@$ from most recent calibration ________
$\Delta H_@$ from check against dry gas meter __________
Nomograph check:
If $\Delta H_@ = 1.80$, TM [illegible]0°F, % H_2O = 10%, $P_s/P_m = 1.00$,
C = 0.95 (0.55)

If C = 0.95, TS = 200°F, DN = 0.375, Δp
reference = 1.17 (0.118)

Align $\Delta p = 1.0$ with $\Delta H = 10$; @$\Delta p = 0.01$, ΔH = 0.1 (0.1)
For nomograph set-up:
Estimated meter temperature _____ °F estimated
value of P_s/P_m __________
Estimated moisture content _____ % how estimated? _____
C factor _____ estimated stack temperature _____ °F
desired nozzle diameter ________
Stack thermometer checked against ambient temperature? _____
Leak test performed before start if sampling? ______
rate ______ cfm @ ______ in. Hg.

8.14 GENERAL/SAMPLING SYSTEM

Sampling method (e.g., EPA 5) ____________
Modifications to standard method ____________
____
Pump type: fibervane with in line oiler ________
carbon vane ________ diaphragm ________
Probe liner material _____ heated _____ entire length _____
Type "S" pitot tube? ________ other ________
Pitot tube connected to: inclined manometer ______
or magnehelic gage ____________
range _____ approx. scale length _____ divisions _____
Office meter connected to: inclined manometer _____
or magnehelic gage ______ range ______
approx. scale length ______ divisions ______
Meter box brand ______ sample box brand ______
Recent calibration of orifice meter-dry gas meter? ______
pitot tubes ______ nozzles ______
thermometers or thermocouples? ____ magnehelic gages? ____
Number of sampling points/traverse from Fed. Reg. ______
number to be used __________
Length of sampling time/point desired ________
time to be used ____________

8.15 SAMPLING

(Use one sheet for each run if necessary) Run # ______

Probe-sample box movement technique:
Is nozzle sealed when probe is in stack with pump turned off? ________
Is care taken to avoid scraping nipple or stack wall? ______
Is an effective seal made around probe at port opening? ________
Is probe seal made without disturbing flow inside stack? ________
Is probe moved to each point at the proper time? ______
Is probe marking system adequate to properly locate each point? ________
Was nozzle and pitot tube kept parallel to stack wall at each point? ________
If probe is disconnected from filter holder with probe in the stack on a negative pressure source, how is particulate matter in the probe prevented from being sucked back into the stack? ________
If filters are changed during a run, was any particulate lost? ________
Meterbox operation:
Is data recorded in a permanent manner ______
are data sheets complete? ______
Average time to reach isokinetic rate at each point ______
Is nomograph setting changed when stack temperature changes significantly? ______
Are velocity pressures (Δ_p) read and recorded accurately ______
Is leak test performed at completion of run? ____ cfm ____ ° ____ in. Hg.
Probe, filter holder, impingers sealed adequately after test? ________
General content on sampling techniques ________
If Orsat analysis is done, was it: from stack ________
from integrated bag? ________
Was bag system leak tested? ________ was orsat leak tested? ______ check against air? ______
If data sheets cannot be copied, record: approximate stack temperature ________ °F.
nozzle dia. ______ in. volume metered ______ ACF
first 8 Δ_p readings ____ ____ ____ ____ ____ ____ ____ ____

If the observer is satisfied with all sampling procedures during the first run, then during the second run time will be spent observing the process monitors, with the exception of checking the sampling team at the end of the sampling period. During the second run, two 6-minute visible emission readings should be made with a check of the facility operations between readings. The observer should be satisfied that the facility data recorded are truly representative of the facility operations.

A visual observation of the particulate buildup on the filter and in the acetone rinse from the first two tests should be correlated to the visible emission readings or transmissometer data. This comparison of particulate collected will be valid only if the sample volumes were approximately the same. If the particulate catch on the filter and in the acetone rinse for the second test was consistent or greater than the visible opacity correlated to the first run, then the observer might need to spend more time overseeing the facility operations. If the second run, when correlated to the opacity, is less than the first test, more time might be spent in observing the emission test procedures for the third run.

Regardless of the main emphasis of the third run, the observer should still perform certain observations. The observer again should check all facility operations before testing. Two 6-minute visible emission readings should be made with a check of the facility operation inbetween. The sample recovery of all tests should be witnessed, and the apparent particulate catch compared to the opacity readings. The additional time can be spent by the observer checking suspected weak points or problem areas.

Recovering and Analyzing the Sample—The observer should be present during sample recovery. It is imperative that the sample recovery and analysis be done under standard procedures and that each step be well documented. The report may ultimately be subject to the requirements of the Rules of Evidence. Therefore, the observer should have a sample recovery checklist to ensure that all tasks have been performed properly.

To reduce the possibility of invalidating the results, all of the sample must be carefully removed from the sampling train and placed in sealed, nonreactive, numbered containers. It is recommended that the sample be delivered to the laboratory for analysis on the same day that the sample is taken. If this is impractical, all the samples should be placed in a carrying case (preferably locked) in which they are protected from breakage, contamination, loss, or deterioration.

The samples should be properly marked to assure positive identification throughout the test and analysis procedures. The Rules of Evidence require impeccable identification of samples, analysis of which may be the basis of future evidence. An admission by a lab analyst that he could not be positive whether he analyzed sample 6 or sample 9, for example, could destroy the validity of an entire report.

Positive identification also must be provided for the filters used in any specific test. All identifying marks should be made before taring. Three or more digits should suffice to ensure the uniqueness of a filter for many years. The ink used for marking must be indelible and unaffected by the gases and temperatures to which it will be subjected. If any other method of identification is desired, it should be kept in mind that the means of identification must be positive and must not impair the function of the filter.

Finally, each container should have a unique identification to preclude the possibility of interchange. The number of a container should be recorded on the analysis data sheet associated with the sample throughout the test and analysis.

Samples should be handled only by persons associated in some way with the task of analysis. A good general rule to follow is "the fewer hands the better," even though a properly sealed sample may pass through a number of hands without affecting its integrity.

It is generally impractical for the analyst to perform the field test. The Rules of Evidence, however, require that a party be able to prove the chain of custody of the sample. For this reason, each person must have documented from whom he received the sample and to whom he delivered it. This requirement is best satisfied by having each recipient sign a standard chain of custody sheet initiated during the sample recovery.

To preclude any omissions of proper procedures after the sample recovery, the observer should have a sample transport and analytical checklist:

8.16 SAMPLE RECOVERY

General environment – clean up area ____________
Wash bottles clean? ____ brushes clean? ____ brushes rusty ____
Jars clean? ____ acetone grade ____ residue on evap. spec. ____
Filter handled ok? ________ probe handled ok? ________
impingers handled ok? ____________
After cleanup: filter holder clean ____ probe liner clean? ____
nozzle clean? ____ impingers clean? ____ blanks taken ____
Description of collected particulate ____________
Silica gel all pink? run 1 ____ run 2 ____ run 3 ____
Jars adequately labeled? ____ jars sealed tightly? ____
Liquid level marked on jars? ____ jars locked up? ____
General comments on entire sampling project:

Was the test team supervisor given the opportunity to read over this checklist? ____________
Did he do so?
Observer's name ____________ title ____________
Affiliation ____________ signature ____________

Potential sources of error in the analysis lie in the contamination of the sample, in the analyzing equipment, procedures, and documentation of results. Since the analysis is often performed at a lab distant from the plant site, the observer is often not present at the sample analysis. If there is any question in the observer's mind about the analyst's ability to adhere to good analytical practices in analyzing and in reporting data, the observer has two recourses: he may be present during analysis or he may require the analysis be done by a certified laboratory if one is available. This is, however, an unnecessary burden and should not be done as a general rule.

During the analysis, any remaining portions of the sample should remain intact and placed in a safe place until the acceptance of the final report. Laboratory equipment, especially the analytical balance, should have been calibrated immediately before the sample weighing. The laboratory data and calculations must be well documented and kept in such a manner that the agency can inspect the recording of any analysis upon request.

As noted in the lectures for this course, the observer should be aware of analytical tricks that can be used to bring a marginal test to within ± 10% of 100% isokinetic. Care should be taken that the value for the nozzle diameter, or C_p, does not change. Also, the weight of the impinger catch and silica gel for the determination of B_{ws} should not be changed to accommodate a % isokinetic value. It has been suggested that to ensure an unbiased test, the observer could supply the source tester with his own preweighed filter and preweighed amount of silica gel. This may be extreme, but necessary in special cases.

Submitting the Report—Upon completion of the compliance field test work, the observer can begin the final task of determining the adequacy of the compliance test data. He will be required to write an observer's report for attachment with the source tester's report. The facility operation, the data, and the field checklists should provide the observer with sufficient information to determine the representativeness of the process and control equipment operation and the sample collection. All minimum conditions should have been met. If the observer suspects a bias in the results, this bias should be noted. A resulting bias that can only produce emission results higher than the true emissions would not invalidate the results if the plant were determined to be in compliance. Therefore, any bias that may occur should be listed along with the suspected direction of the bias.

The test team supervisor is responsible for the compilation of the test report and is usually under the supervision of a senior engineer who reviews the report for content and technical accuracy. Uniformity of data reporting will enable the agency to review the reports in less time and with greater efficiency. For this reason, a report format should be given to the test team supervisor along with the other agency guidelines.

The first review of the test report should be made by the observer. The observer should check all calculations and written material for validity. One of the greatest problems in compliance testing is in the calculation errors made in the final report. Several agencies have gone to the extreme of having the observer recalculate the results from the raw data to find any error more easily. Errors should be noted along with comments by the observer. Although the conclusions in the observer's report are not the final authority, they should carry the greatest amount of weight in the final decision concerning the representativeness of the test.

Because of the importance of the observer's report and the possibility that it may be used as evidence in court, the observer should use a standard report format that will cover all areas of representativeness in a logical manner. An example of an observer's report format is presented.

8.17 OBSERVER'S REPORT FORMAT

Cover

1. Plant name and location (Federal AQCR)
2. Source sampled
3. Date sampled
4. Testing firm
5. Control agency

Certification

1. Certification by observer(s)
2. Certification by author if not observer
3. Certification by key agency personnel

Introduction

1. Agency name
2. Purpose for observer's report
3. Purpose for test
4. Plant name, location and process type
5. Test dates
6. Pollutants tested
7. Applicable regulations
8. Agency sections and personnel directly involved

Summary of Representativeness of Data

1. Compliance test protocol
2. Calibration of sampling equipment
3. Process data
4. Control equipment data
5. Sampling procedures
7. Analytical procedures
8. Compliance test report

Facility Operation

1. Description of process and control device
2. Baseline conditions
3. Observer's facility data (checklists)
4. Representativeness of process and control device
5. Baseline conditions for agency inspector

Sampling procedures

1. Acceptability of sample port and point locations
2. Compliance test protocol
3. Calibration of sampling equipment
4. Observer's sampling data (checklist)
5. Representativeness of sampling
6. Observer's sample recovery data (checklist)
7. Representativeness of recovered sample
8. Observer's analytical data
9. Representativeness of sample

Compliance Test Report

1. Introduction
2. Summary of results
3. Facility operation
4. Sampling procedures
5. Appendices

Appendices

A. Copy of pertinent regulations
B. Related correspondence
C. Compliance test protocol
D. Observer's checklists
E. Observer's test log
F. Other related material

In addition to the determination of representative data for the compliance test, the observer should report all conditions under which the facility must operate in the future to maintain their conditional compliance status. These conditions will be reported to the facility as conditions of their acceptance.

These reports and the conditions of the compliance acceptance will provide any agency inspector with sufficient data to conduct all future facility inspection trips.

Chapter 9
Additional Topics

A. SOURCE SAMPLING TRAIN CONFIGURATIONS

The Environmental Protection Agency has developed testing procedures to evaluate the standard of performance for stationary sources. The *Federal Register*, August 18, 1977, describes the reference methods to be used for the performance test and outlines in Reference Method 5 the procedures and equipment to be followed in determining particulate emissions from stationary sources. An equivalent method subject to approval by the Administrator may be used when emissions from a given facility are not susceptible to being measured by Reference Method 5. The Reference Method determination of particulate emissions is based on the *Federal Register* definition of "particulate" in Subpart D §60.41 (c):

> "Particulate matter" means any finely divided liquid or solid material, other than uncombined water, as measured by Method 5.

This is a legal definition. A source test engineer must also have a scientific definition.

Reference Method 5, as written in the August 18, 1977 *Federal Register*, is presented schematically in Figure 9-1.

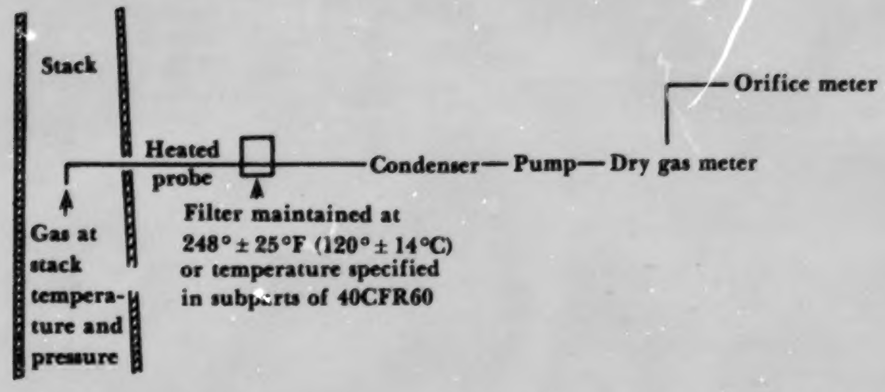

Stack
Heated probe
Condenser— Pump— Dry gas meter
Orifice meter
Gas at stack temperature and pressure
Filter maintained at 248° ± 25°F (120° ± 14°C) or temperature specified in subparts of 40CFR60

Figure 9-1. Schematic diagram of Reference Method 5

Analytical procedures for the method require the following:

1. Filter glass mat and particulates be desiccated to constant weight ± 0.5 mg.
2. Probe, nozzle, and filter holder be washed with acetone.
   a. Acetone blank (100 ml) evaporated at room temperature and pressure.
   b. Acetone and particulates evaporated at room temperature and pressure in a tared weighing bottle.
   c. Particulates desiccated and weighed to constant weight ± 0.5 mg.
3. Silica gel weighed to nearest gram.
4. Volume H_2O in condenser measured and recorded. H_2O discarded.

The schematic sampling train and the outline of the analytical procedure required constitute a scientific definition of the "particulate." The temperature and pressure at which a solid or liquid particulate is caught on the filter mat are defined. Also given are the portions of the sampling train which are analyzed for this particulate.

There are a number of other source sampling methods available for isokinetic sampling. The configuration of the sampling train and the analytical procedures employed can effect the definition of "particulate matter."

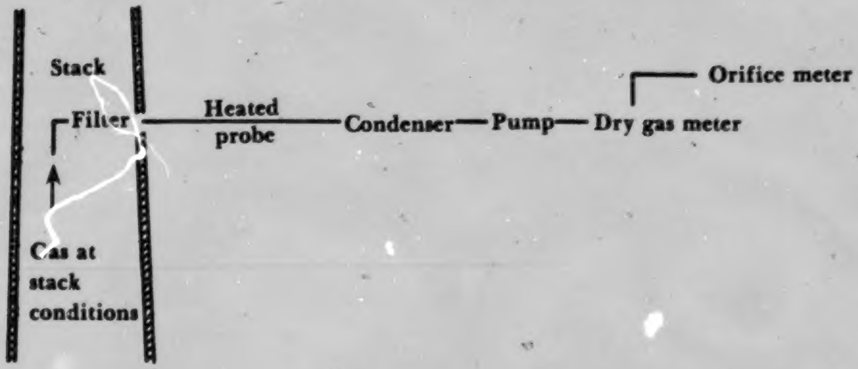

Stack
Filter
Heated probe
Condenser—Pump— Dry gas meter
Orifice meter
Gas at stack conditions

Figure 9-2. Schematic diagram of an in-stack train.

The In-Stack Filter

A schematic diagram of an in-stack train is illustrated in Figure 9-2. The filter is maintained at stack temperature and pressure. The analytical procedures are an important factor in defining the total "particulate matter" sampled by the system.

Typical analytical procedures assess particulate matter on the filter mat only. This system would, therefore, define only solid or liquid particulates at stack conditions. Particulates penetrating the filter and settling in the probe or condenser might be ignored. Gaseous pollutants that might be solid or liquid at 248° ± 25°F would be trapped in the condenser. If analysis excludes the condenser catch, these particulates would not be part of the "particulate matter." The gases condensing in a water trap could become complex and form psuedo-particulate that could bias the sample. The use of this type of system must be carefully evaluated in the context of the test objectives and source operating conditions.

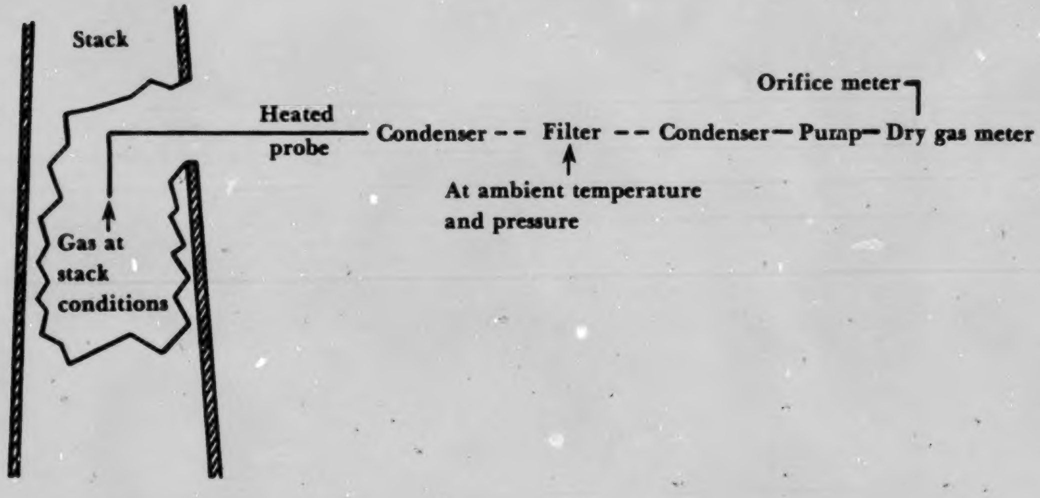


Figure 9-3. Schematic diagram of EPA Method 5 (Modification No. 1)

EPA Method 5 (Modification No. 1)

The schematic for this modification is illustrated in Figure 9-3. The system uses an out-of-stack filter at ambient temperature and pressure. The filter is located between the first and second condenser. This is similar to the diagram for *Federal Register* Method 8. It traps gases and liquids and solids in the condenser and on the filter. The system could be used for particulate sampling. The filter particulate matter would, however, be trapped at a temperature much lower than the 248° ± 25°F recommended for Method 5. Analytical procedures for particulate matter in the first and second condensers could be biased by psuedo-particulate formation. When used for particulate testing, this system must be evaluated in the context of test objectives and source operations.

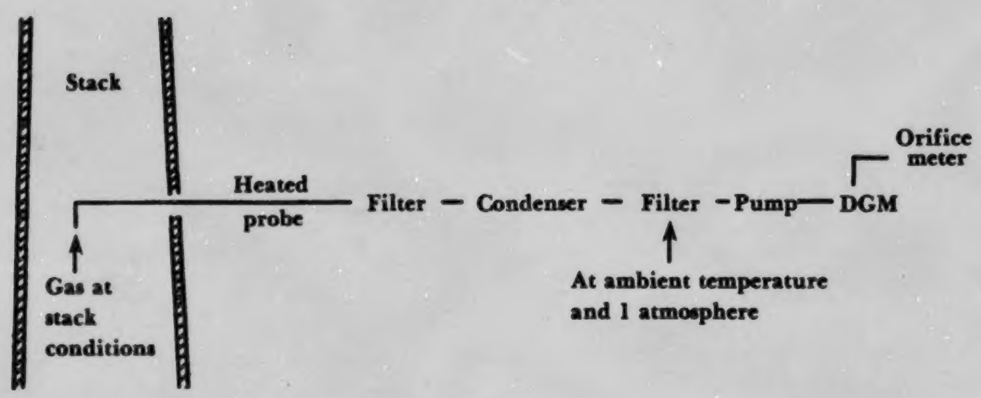

Stack
Orifice meter
Heated probe
Filter
Condenser
Filter
Pump
DGM
Gas at stack conditions
At ambient temperature and 1 atmosphere

Figure 9-4. EPA Method 5 (Modification No. 2)

EPA Method 5 (Modification No. 2)

This modification depicted in Figure 9-4 shows filters located both behind and in front of the condenser. The front filter is maintained at *Federal Register* recommendations of 248° ± 25°F. The second filter is at ambient temperature and pressure. This system would trap particulates on the filters and in the condenser. The selective analysis of various parts of the train could be very important. The system could be subject to the biases noted in the other systems. It can, however, give a full assessment of particulates emitted at a source.

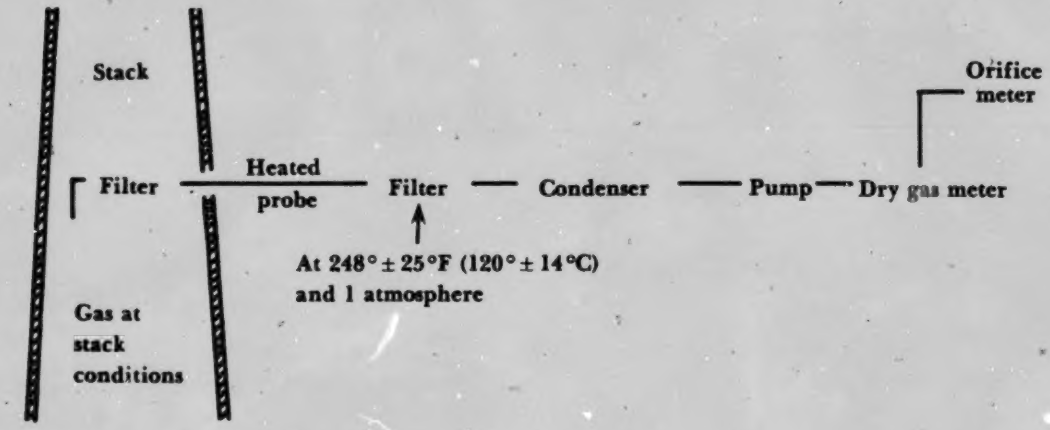

Stack
Orifice meter
Filter
Heated probe
Filter
Condenser
Pump
Dry gas meter
At 248° ± 25°F (120° ± 14°C) and 1 atmosphere
Gas at stack conditions

Figure 9-5. Combined system.

The diagram (Figure 9-5) shows an in-stack filter backed up with an out-of-stack filter maintained at 248° ± 25°F. The system could assess in-stack particulates, Method 5 particulates, and ambient particulates. The scope of particulates measured would depend upon the analytical procedure. This system could be a useful research tool.

Summary

The Clean Air Act requires that air pollution be prevented and controlled. The Federal Regulations emanating from this for control of source emissions require source emissions performance tests. Particulate emissions testing procedures are outlined in *Federal Register*, August 18, 1977, Method 5. Alternative procedures may be used if the Method 5 test can not be performed at a given facility; these alternative procedures must have Administrator approval.

The regulations define "particulate matter" in terms of Reference Method 5. An examination of the Method 5 system gives insights into the scientific definition of particulate as assessed by this sampling method. Alternative systems to Method 5 can have an effect on the definition of "particulate matter." "Particulate matter," as defined by these systems, depends upon the temperature and location of the collection filter and the selective analysis of sampling train sections. Any sampling system used for a particulate emissions performance test must be capable of assessing the best available system of emissions reduction. The sampling train must be designed and analyzed within the context of these objectives and source operating conditions.

B. REPORTING IN UNITS OF THE STANDARD: F-FACTOR METHODS

F Factors: Introduction

The use of the F factor in calculating particulate emission levels from *new* stationary sources was promulgated in the October 6, 1975 *Federal Register*. The F factor is intended to reduce the amount of data necessary to calculate particulate emissions in terms of the standard expressed as pounds per million Btu heat input (lbs./10^6 Btu). As mentioned earlier, there are currently three types of standards for particulate mass

concentration standards	c_s	(ppm, grains/ft^3, grams/dscm)
pollutant mass rate standards	pmr_s	(lbs/hr, Kg/hr)
process rate standards	E	(lbs./10^6 Btu, ng/J, lbs/ton)

The emission rate, in terms of the units given in the New Source Performance Standards, is related to concentration and mass rate in the following manner

(Eq.9-1)

$$E = \frac{pmr_s}{Q_H} = \frac{c_s Q_s}{Q_H}$$

where Q_s is, of course, the stack gas volumetric flow rate (units of ft.^{3}/hr., Nm^3/hr).

and

Q_H is the heat input rate, the rate at which combusted fuel supplies heat to the boiler or other heat utilization system (Btu/hr, Kcal/hr)

By dimensional analysis, it can be seen that the units of E in terms of pollutant mass per unit of heat input are

(Eq.9-2)

$$E = \frac{lbs\ /hr}{10^6 Btu/hr} = \frac{(lbs\ /ft^3)(ft^3/hr)}{10^6 Btu\ /hr} = lbs\ /10^6 Btu$$

To obtain emission rates in units of lbs/10^6Btu, it is necessary for the source sampler to obtain the following information:

1. pollutant concentration, c_s
    a. pollutant mass captured
    b. dry gas volume sampled
2. effluent volumetric flow rate, Q_s
    a. stack gas velocity
    b. stack temperature
    c. stack pressure
    d. dry gas composition (Orsat) % CO_2, % O_2, % N_2
    e. moisture content
3. heat input rate, Q_H
    a. fuel input rate
    b. proximate analysis of fuel

Although all of the quantities for c_s and Q_s are obtained in a source test, the quantities making up the heat input rate Q_H may not be easily obtained. Once obtained, their accuracy may be in doubt since the source sampler usually is not able to calibrate or check the accuracy of the source fuel flow meter. The representative nature of the fuel sample and the accuracy of the fuel analysis itself may be difficult to determine. Consequently, a factor, based on simple principles of combustion was developed to avoid many of the problems involved in the calculation of E. By using the F factor, E may be simply obtained from the formula

(Eq.9-3)

$$E = c_s F\left(\frac{20.9}{20.9 - \%O_2}\right)$$

The F factor essentially replaces the ratio Q_s/Q_H and the term in brackets is merely an excess air correction.

The F factor is useful in calculating emissions for particulate matter. In the case of its application to continuous monitoring instrumentation for gases, it is even more valuable. The use of the F factor and its variants (F_c and F_w factors), in reporting continuous monitoring data in terms of lbs /10^6Btu heat input, enables the source operator to monitor only the pollutant gas concentration and the O_2 or CO_2 concentration. Without this method, it would be necessary to continuously monitor stack gas velocity, temperature, fuel input rate, etc. This would be possible, but impractical and expensive.

In the sections below, the derivation and uses of the F factor, will be discussed further. Also, the requirements of 40CFR60.46 for the use of the F factor in Method 5 will be given.

Derivation of the F Factor Method

Before proceeding with the derivation of the F factor, it is necessary to give a few definitions used in combustion analysis, namely those for "proximate analysis," "ultimate analysis," and "gross calorific value."

Proximate analysis — a fuel analysis procedure that expresses the principal characteristics of the fuel as

1. % moisture
2. % ash
3. % volatile matter
4. % fixed carbon

} Total 100%

5. % sulfur
6. heating value (Btu/lb.)
7. ash fusion temperature

Ultimate analysis — the determination of the exact chemical composition of the fuel without paying attention to the physical form in which the compounds appear. The analysis is generally given in terms of percent hydrogen, percent carbon, percent sulfur, percent nitrogen, and percent oxygen.

Gross Calorific Value (GCV) — also termed the "high heating value." The total heat obtained from the complete combustion of a fuel. Referred to a set of standard conditions. The GCV is obtained in the proximate analysis as the "heating value."

These definitions generally apply to the fuel "as received" at the plant.

If one considers the volume of gas generated by the combustion of a quantity of fuel, the F factor relationship can be easily obtained. First, defining V_t as the theoretical volume of dry combustion products generated per pound of fuel burned in dscf/lb, the following equality can be made

(Eq.9-4)
$$\frac{Q_s}{Q_H}\begin{pmatrix}\text{excess air}\\ \text{correction}\end{pmatrix} = \frac{V_t}{GCV}.$$

Dimensionally, this says

$$\frac{ft^3/hr}{Btu/hr} = \frac{ft^3}{Btu}.$$

Q_s and Q_H can be determined at the source. V_t is obtained from the ultimate analysis of the fuel.

Remembering the first equation given in this section,

$$E = \frac{c_s Q_s}{Q_H} \quad \text{and substituting in Equation 9-4,}$$

$$E = \frac{c_s V_t}{GCV}\ \frac{1}{\begin{pmatrix}\text{excess air}\\ \text{correction}\end{pmatrix}}$$

The quantity V_t/GCV is then defined as the F_d factor and the following simplified equation is obtained.

(Eq.9-5)

$$E = c_s F_d \frac{1}{\left(\begin{matrix}\text{excess air}\\ \text{correction}\end{matrix}\right)}$$

For EPA Method 5, the oxygen concentration of the source must be determined simultaneously and at the same traverse. Since the excess air correction using percent oxygen is

$$\left(\frac{20.9 - \%O_2}{20.9}\right),$$

the equation to be used for calculating emissions for EPA Method 5 is

(Eq.9-6)

$$E = c_s F_d \left(\frac{20.9}{20.9 - \%O_2}\right).$$

As mentioned earlier, there are different types of F factors. The differences arise in the way in which the excess air corrections are determined. For example, the F_c factor is used when the percent CO_2 is determined instead of percent O_2. (Note: the F_c factor is not promulgated for use in calculating particulate emissions, although it may be used in reporting continuous monitoring data for gases). A table of F factors is given for reference.

It should also be noted that the F factor may be used with the percent O_2 and c_{ws} determined on a wet basis if the moisture content B_{ws} of the stack is known:

(Eq.9-7)

$$E = c_{ws} F_d \left(\frac{20.9}{20.9(1 - B_{ws}) - \%O_{2w}}\right).$$

Note: The subscript w stands for measurements made on a wet basis. All other measurements are assumed to be made on a dry basis.

Factor	Excess Air Units	Measurement Required for Emissions Determination	Calculations	Comments
F_d	$\frac{dscf}{10^6 Btu}$	$\%O_2$ (dry basis)	$E = c_s F_d \left[\frac{20.9}{20.9 - \%O_{2d}} \right]$	c_s determined on dry basis
F_c	$\frac{dscf}{10^6 Btu}$	$\% CO_2$ (dry or wet basis)	$E = c_s F_c \left[\frac{100}{\% CO_2} \right]$	c_s on dry or wet basis consistent with CO_2 measurement
F_w	$\frac{wscf}{10^6 Btu}$	$\% O_2$ (wet basis)	$E = c_{ws} F_w \left[\frac{20.9}{20.9(1 - B_{wa}) - \%O_{2w}} \right]$	The "wet" F factor, c_{ws} and $\%O_2$ on wet basis B_{wa} = average moisture content of ambient air
F_o	—	—	$F_o = \frac{20.9}{100} \frac{F_d}{F_c} = \frac{20.9 - \%O_2}{\%CO_2}$	Miscellaneous factor useful for checking Orsat data

Table 9-1. F factors.

Calculation and Tabulation of F Factors

The F_d factor method carries with it the assumption that the ratio, V_t/GCV, the ratio of the quantity of dry effluent gas generated by combustion to the gross calorific value, is constant within a given category. This ratio, of course, is the F_d factor.

V_t is determined from the stoichiometry of the combustion reaction; i.e., if a hydrocarbon is burned in air, gaseous products will result, the volumes of which can be calculated. For example,

$$\underbrace{C_3H_8}_{\text{propane}} + \underbrace{O_2 + N_2}_{\text{air}} \rightarrow \underbrace{CO_2\uparrow + H_2O\uparrow + N_2\uparrow}_{\text{gases}} .$$

For each pound of fuel undergoing perfect combustion, a known amount of gaseous products will result. Using the stoichiometric relationships resulting from chemical reactions similar to the example above, and given the gross calorific value of the fuel per pound, the following relationships have been developed for the F factors.

(Eq.9-8)

$$F_d = \frac{227.0(\%H) + 95.7(\%C) + 35.4(\%S) + 8.6(\%N) - 28.5(\%O)}{GCV} \quad \textit{(metric units)}$$

$$F_d = \frac{10^6[3.64(\%H) + 1.53(\%C) + 0.57(\%S) + 0.14(\%N) - 0.46(\%O)]}{GCV} \quad \textit{(English units)}$$

(Eq.9-9)

$$F_c = \frac{20.0(\%C)}{GCV} \quad \textit{(metric units)}$$

$$F_c = \frac{321 \times 10^3(\%C)}{GCV} \quad \textit{(English units)}$$

(Eq.9-10)

$$F_w = \frac{347.4(\%H) + 95.7(\%C) + 35.4(\%S) + 8.6(\%N) - 28.5(\%O) + 13.4(\%H_2O)}{GCV_w} \quad \textit{(metric units)}$$

$$F_w = \frac{10^6[5.56(\%H) + 1.53(\%C) + 0.57(\%S) + 0.14(\%N) - 0.46(\%O) + 0.21(\%H_2O]}{GCV_w} \quad \textit{(English units)}$$

If the source utilizes a combination of fossil fuels, a simple addition procedure can be used to compute the F factor.

(Eq.9-11) $$F = xF_1 + yF_2 + zF_3$$

where

x,y,z = *the fraction of total heat input derived from gaseous, liquid, and solid fuels, respectively.*

F_1,F_2,F_3 = *the value of F for gaseous, liquid, and solid fossil fuels, respectively.*

Several F factors have been calculated for various types of fossil and waste fuels. It has been found that for a given type of fuel the F factor does not vary over a significantly large range. For example, for bituminous coal, the F_d factors were found to range from values of 9750 dscf/10^6 to 9930 dscf/10^6Btu, giving a maximum deviation from the midpoint value of 9820 dscf/10^6Btu of less than 3 percent. In general, it has been reported that the F_d factor can be calculated to within a ± 3 percent deviation and the F_c factor can be calculated to within a ± 5.9 percent deviation. The calculated factors are given in the following table.

F Factors for Various Fuels [a,b]

FUEL TYPE	F_d dscf/10^6 Btu	F_w wscf/10^6 Btu	F_c scf/10^6 Btu	F_o
Coal				
Anthracite	10140 (2.0)	10580 (1.5)*	1980 (4.1)	1.070 (2.9)
Bituminous	9820 (3.1)	10680 (2.7)	1810 (5.9)	1.140 (4.5)
Lignite	9900 (2.2)	12000 (3.8)	1920 (4.6)	1.0761 (2.8)
Oil	9220 (3.0)	10360 (3.5)	1430 (5.1)	1.3461 (4.1)
Gas				
Natural	8740 (2.2)	10650 (0.8)	1040 (3.9)	1.79 (2.9)
Propane	8740 (2.2)	10240 (0.4)	1200 (1.0)*	1.51 (1.2)*
Butane	8740 (2.2)	10430 (0.7)	1260 (1.0)	1.479 (0.9)
Wood	9280 (1.9)*	--------	1840 (5.0)	1.05 (3.4)
Wood Bark	9640 (4.1)	--------	1860 (3.6)	1.056 (3.9)
Paper and Wood Wastes[c]	9260 (3.6)		1870 (3.3)	1.046 (4.6)
Lawn and Garden Wastes[d]	9590 (5.0)		1840 (3.0)	1.088 (2.4)
Plastics				
Polyethylene	9173		1380	1.394
Polystyrene	9860		1700	1.213
Polyurethane	10010		1810	1.157
Polyvinyl Chloride	9120		1480	1.286
Garbage[e]	9640 (4.0)		1790 (7.9)	1.110 (5.6)
Miscellaneous				
Citrus rinds and seeds	9570		1920	1.020
Meat scraps, cooked	9210		1540	1.252
Fried fats	8939		1430	1.310
Leather shoe	9530		1720	1.156
Heel and sole composition	9480		1550	1.279
Vacuum cleaner catch	9490		1700	1.170
Textiles	9354		1840	1.060
Waxed milk cartons	9413		1620	1.040

[a] Numbers in parentheses are maximum deviations (%) from the midpoint F factors.

[b] To convert to metric system, multiply the above values by 1.123×10^{-4} to obtain scm/10^6 cal.

[c] Includes newspapers, brown paper, corrugated boxes, magazines, junk mail, wood, green logs, rotten timber.

[d] Includes evergreen shrub cuttings, flowering garden plants, leaves, grass.

[e] Includes vegetable food wastes, garbage (not described).

* All numbers below the asterisk in each column are midpoint values. All others are averages.

Application of the F Factor to EPA Method 5

It appears that much confusion has arisen with regard to the use of the F factor in reporting Method 5 data. In the *Code of Federal Regulations,* 40CFR60.46, under Test Methods and Procedures for the New Source Performance Standards, emissions expressed in terms of lb/10^6 Btu are to be determined using the formula

(Eq.9-12)
$$E = c_s F_d \frac{20.9}{20.9 - \%O_2}$$

Reproduced below is: **"PART 60—STANDARDS OF PERFORMANCE FOR NEW STATIONARY SOURCES."**

Subpart D—Standards of Performance for Fossil-Fuel Fired Steam Generators

§ 60.46 Test methods and procedures.

(a) The reference methods in Appendix A of this part, except as provided in § 60.8(b), shall be used to determine compliance with the standards as prescribed in §§ 60.42, 60.43, and 60.44 as follows:

(1) Method 1 for selection of sampling site and sample traverses.

(2) Method 3 for gas analysis to be used when applying Reference Methods 5, 6 and 7.

(3) Method 5 for concentration of particulate matter and the associated moisture content.

(4) Method 6 for concentration of SO_2, and

(5) Method 7 for concentration of NO_x.

(b) For Method 5, Method 1 shall be used to select the sampling site and the number of traverse sampling points. The sampling time for each run shall be at least 60 minutes and the minimum sampling volume shall be 0.85 dscm (30 dscf) except that smaller sampling times or volumes, when necessitated by process variables or other factors, may be approved by the Administrator. The probe and filter holder heating systems in the sampling train shall be set to provide a gas temperature no greater than 433 K (320°F).

(c) For Methods 6 and 7, the sampling site shall be the same as that selected for Method 5. The sampling point in the duct shall be at the centroid of the cross section or at a point no closer to the walls than 1 m (3.28 ft). For Method 6, the sample shall be extracted at a rate proportional to the gas velocity at the sampling point.

(d) For Method 6, the minimum sampling time shall be 20 minutes and the minimum sampling volume 0.02 dscm (0.71 dscf) for each sample. The arithmetic mean of two samples shall constitute one run. Samples shall be taken at approximately 30-minute intervals.

(e) For Method 7, each run shall consist of at least four grab samples taken at approximately 15-minute intervals. The arithmetic mean of the samples shall constitute the run value.

(f) For each run using the methods specified by paragraphs (a)(3), (a)(4), and (a)(5) of this section, the emissions expressed in ng/J (lb/million Btu) shall be determined by the following procedure:

$$E = CF(20.9/20.9 - \text{percent } O_2)$$

where:

(1) E=pollutant emission ng/J (lb/million Btu).

(2) C=pollutant concentration, ng/dscm (lb/dscf), determined by method 5, 6, or 7.

(3) Percent O_2=oxygen content by volume (expressed as percent), dry basis. Percent oxygen shall be determined by using the integrated or grab sampling and analysis procedures of Method 3 as applicable.

The sample shall be obtained as follows:

(i) For determination of sulfur dioxide and nitrogen oxides emissions, the oxygen sample shall be obtained simultaneously at the same point in the duct as used to obtain the samples for Methods 6 and 7 determinations, respectively [§ 60.46(c)]. For Method 7, the oxygen sample shall be obtained using the grab sampling and analysis procedures of Method 3.

(ii) For determination of particulate emissions, the oxygen sample shall be obtained simultaneously by traversing the duct at the same sampling location used for each run of Method 5 under paragraph (b) of this section. Method 1 shall be used for selection of the number of traverse points except that no more than 12 sample points are required.

(4) F=a factor as determined in paragraphs (f) (4), (5) or (6) of § 60.45.

(g) When combinations of fossil fuels or fossil fuel and wood residue are fired, the heat input, expressed in watts (Btu/hr), is determined during each testing period by multiplying the gross calorific value of each fuel fired (in J/kg or Btu/lb) by the rate of each fuel burned (in kg/sec or lb/hr). Gross calorific values are determined in accordance with A.S.T.M. methods D 2015-66(72) (solid fuels), D 240-64(73) (liquid fuels), or D 1826-64(7) (gaseous fuels) as applicable. The method used to determine calorific value of wood residue must be approved by the Administrator. The owner or operator shall determine the rate of fuels burned during each testing period by suitable methods and shall confirm the rate by a material balance over the steam generation system.

(Sec. 114, Clean Air Act as amended (42 U.S.C. 7414))

[40 FR 46258, Oct. 6, 1975, as amended at 41 FR 53199, Nov. 22, 1976]

There are three points that should be made here:

- Only the dry F factor using percent O_2 for the excess air correction may be used in the calculation. The F_c and F_w factors may not be used.
- The oxygen sample is to be obtained simultaneously with the Method 5 run, at the same traverse points. This essentially requires that an additional probe be placed along with the Method 5 probe and an additional pump be used to obtain an integrated bag sample over the duration of the run. However, only 12 sample points are required. If there are more than 12 traverse points determined by EPA Method 1, an independent integrated gas sampling train could be used to traverse 12 points in the duct simultaneously with the particulate run.
- The procedures in 40CFR60.46 apply to *new* fossil-fuel fired steam generators (new sources are those constructed or modified after August 17, 1971). For existing fossil-fuel steam generators, which are regulated by State standards, the State or local regulations should be checked for application of the F factor method.

Other Uses of F Factors

A. If values for Q_s, the stack gas volumetric flow rate, and Q_H the heat input rate, are obtained during the source test, as they often are, several cross-checks can be made by comparing various calculated F factor values with the tabulated values. Equations that can be used to do this are given below.

(Eq.9-13)

$$F_d(calc) = \frac{Q_s}{Q_H} \frac{(20.9 - \%O_2)}{20.9}$$

(Eq.9-14)

$$F_w\,(calc) = \frac{Q_{sw}}{Q_H} \frac{20.9(1 - B_{wa}) - \%O_{2w}}{20.9}$$

(Eq.9-15)

$$F_c(calc) = \frac{Q_s}{Q_H} \frac{\%CO_2}{100} = \frac{Q_{sw}}{Q_H} \frac{\%CO_{2w}}{100}$$

If, after calculating F_d, F_c, or F_w, a large discrepancy exists between the calculated value and the corresponding value in the table, the original data for Q_s, Q_H, and the Orsat data should be checked. This is an easy way of conducting a material balance check.

B. Using a tabulated value for F_d, F_c, or F_w and the data obtained during the stack test for Q_s and $\%O_2$ or $\%CO_2$, a value of Q_H may be obtained from the equations.

C. If ultimate and proximate analyses are available, they may be used to calculate an F factor using one of the equations. The calculated value can then be checked with the tabulated values and should be within 3 to 5 percent agreement, depending on the type of fuel and type of F factor.

D. The F_o factor may be used to check Orsat data in the field.

The F_o factor is the ratio

(Eq.9-16)

$$F_o = \frac{20.9}{100} \frac{F_d}{F_c}$$

and is equal to

$$F_o = \left(\frac{20.9 - \%O_2}{\%CO_2}\right)$$

the $\%O_2$ and $\%CO_2$ being obtained or adjusted to a dry basis. A value differing from those tabulated would necessitate a recheck of the Orsat data.

Errors and Problems in the Use of F Factors

The following factors may contribute to errors in reporting emissions by using F factors:

- Deviations in the averaged or "midpoint" F factor value itself.
- Errors in the Orsat analysis and the consequent $\%O_2$ and $\%CO_2$ values.
- Failure to have complete combustion of the fuel (complete combustion is assumed in the derivation of all of the F factor methods)
- Loss of CO_2 when wet scrubbers are used—affecting the F_d, F_c and F_w factors. Addition of CO_2 when lime or limestone scrubbers are used—affecting the F_c factor.

The deviations in the F factors themselves have been found to vary no more than about 5 percent within a given fuel category. Since the F factors given are averaged values, differences in the ultimate analysis between fuel samples could easily account for the deviation. The most significant problem in the use of the F factors, however, is in the excess air correction—the use of the Orsat data in calculating the particulate emissions. An error of a few percent in the oxygen concentration could cause a relatively large error in the value of E, or more importantly, could mean the difference between compliance and noncompliance. A recent publication by Mitchell and Midgett (1976), entitled "Field Reliability of the Orsat Analyzer," states

> The results from five collaborative tests of the Orsat Method indicate that the use of Orsat data to determine the molecular weight of flue gases is a valid procedure, but the use of such data routinely to convert particulate catches to such reference conditions as 12% CO_2 and 50% excess air may introduce sizeable errors in the corrected particulate loading....
>
> However, since the use of Orsat data for calculating particulate conversion factors will likely continue it seems prudent to develop procedures to check the reliability of Orsat data. One procedure, that could be instituted without affecting either the cost or time of a source test, would be to require that if the Orsat data is to be used for calculating a particulate conversion factor, then the integrated flue gas sample must be independently analyzed by at least two analysts and their results for each gas component must agree within a certain volume percent—say 0.3%—before they can be used to calculate the conversion factor.

Since the F factor method has been developed assuming complete combustion of the fuel, incomplete combustion will cause an error. However, if the $\%CO$ is determined in the flue gas, some adjustment can be made to minimize this error.

(Eq.9-17) $$(\%CO_2)_{adj} = \%CO_2 + \%CO$$

(Eq.9-18) $$(\%O_2)_{adj} = \%O_2 - 0.5\ \%CO$$

By making these adjustments, the error amounts to minus one-half the concentration of CO present.

The loss of CO_2 in wet scrubbing systems will also have an effect on the F factors. A 10% loss of CO_2 will produce an approximate 10% error in the F_c factor. Since the F_d factor (O_2 correction) is based on source combustion products, its value will also be affected by the loss of CO_2. If the gas stream has 6% O_2 and 1.4% CO_2 is lost in the scrubber, the error will be about plus 2.8%. The F_w factor is not applicable after wet scrubber since the moisture content would have to be independently determined.

In general, the greatest errors associated with the F factor method are those that would be associated with the excess air correction. Collaborative testing programs have found that such errors can range as high as 35% when emission rates are corrected to 12% CO_2. F factors can be a valuable tool in calculating source emissions in terms of the New Source Performance Standards; however, care should be taken in their application. Considerable effort should be given by the source sampler to obtain representative and accurate Orsat data.

C. PARTICLE SIZING

Particle Sizing

A particle has several important properties. These are mass, dimension, chemical composition, aerodynamic properties, and optical properties. The primary distinguishing feature of any particle is the particle size. The most widely used unit describing particle size is the micron.

$$1 \text{ micron } (\mu) = 0.001 \text{ mm} = 10^{-4} \text{cm} = 10^{-6} \text{ meter}$$

Particle size may be determined by a variety of analytical techniques. The analysis of particle size is misleading since in practice these techniques do not measure actual particle size, rather they measure particle properties related to the particle size and shape. Analytical or empirical relationships incorporating theoretical principles and assumptions are then employed to assign the particle an "effective size." Particle size analysis is influenced by the extreme diversity of particle shape. Size analysis data can be widely different depending upon the methods employed for analysis. The analytical methods used for size analysis must, therefore, be carefully considered in terms of the objective purpose for which the size analysis is required.

Particle Physical Properties

The term "particle size" generally refers to an "effective size" described as an equivalent or effect diameter. A large amount of empirical and theoretical information has been developed for describing the physical properties of spheres of unit density in dry air. The data can be applied in predicting the physical properties—mass, volume, or settling velocity—for any particle if the particle size can be defined in terms equivalent to the terms used in describing a sphere. The most convenient and frequently used common term is "diameter": the particle size is described in terms of a sphere of equivalent diameter. Assuming that the physical properties of the particle will be similar to those of a sphere of the equivalent diameter and that a physical property (f) is proportional to some power of the diameter(d), the prediction can be made:

(Eq.9-19)

$$f(d) = \alpha d^n$$

where n = a number (determined empirically or theoretically)

α = a shape factor specific for particles of a given shape and composition

This is extremely important for the design of emissions control devices. The important parameters involved in operating and maintaining emissions control devices can be fully evaluated only after adequate particle size information has been obtained.

Particle Motion

The most common and useful particle sizing methods for solid particles suspended in a gas define particle size as an aerodynamic diameter. This allows the prediction of the aerodynamic properties of a particle. These properties are extremely important in designing control equipment to remove particles suspended in a gas emitted to the atmosphere. The procedures employed rely on several principles of fluid dynamics and the calculations made by investigators Stokes and Cunningham. The principles involved will be discussed to aid in understanding the operation of the devices for determining particle aerodynamic diameter.

The Mechanism of Drag for Submerged Particles

The flow phenomena of a nonviscous, incompressible fluid around a submerged object is explained by the Equation of Continuity and Bernoulli's theorem. The diagram in Figure 9-6 illustrates the streamlines of the fluid. The velocity of a fluid molecule perpendicular to a tangent drawn at point I falls to zero. The incompressible fluid particles flowing around the object follow the principles in the equation of continuity; the streamlines come closer together with a resultant increase in acceleration. The acceleration at point II is accompanied by a decrease in pressure as described by Bernoulli, i.e., the net work done on the fluid by pressure must be equal to the net gain in mechanical energy. Fluid mass and energy must be conserved in a nonviscous, incompressible system, therefore, as the fluid flows around the body to point III it releases mechanical energy, increasing the pressure. The fluid decelerates to its original velocity and the system pressure returns to the values at point I. Fluid streamlines in this ideal system are symmetrical in front of and behind the submerged body.

The flow of viscous, compressible fluid around a submerged object may also be examined and understood in the context of the equation of continuity and Bernoulli's theorem. The nonviscous, incompressible fluid flows around the object without losing energy. The viscous, compressible fluid would experience surface

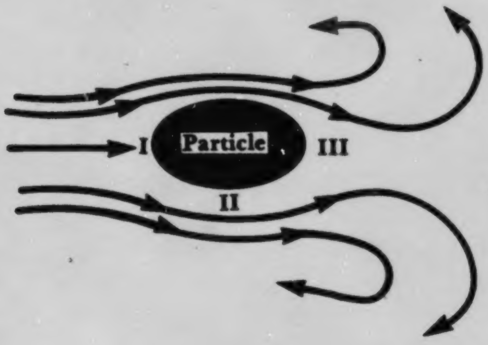


Figure 9-6. Submerged particle.

drag or friction as it passes from point I to point II. The equation of continuity shows that the accelerating fluid would increase the fluid mass per cross-sectional area per unit time passing from point I to point II. The fluid would "pile up" during its flow, increasing the fluid density and changing the Reynolds Number of the fluid. The friction from surface drag dissipates part of the mechanical energy of the fluid as heat. The fluid cannot return mechanical energy as pressure, therefore, fluid pressure at a distance beyond point II is lower than the pressure of the fluid at point I or point III. The Reynolds Number changes are caused by changes in fluid density and viscosity. Increased viscosity creates tangential forces which in conjunction with the opposition forces of higher pressure at point III acting on the accelerated fluid force it to disassociate with the fluid streamlines behind the body. The accelerated fluid must find somewhere to flow since it cannot rejoin the original streamline. The forces acting upon the fluid cause it to flow in a reverse, tangential pattern forming a vortex behind the body. The continued fluid flow around the submerged body with continuously changing Reynolds Number quickly sweeps the vortex formed downstream. A new vortex forms and the interaction of these vortices results in a turbulent wake behind the submerged body. The net effect on the submerged body is frictional and pressure drag.

Stokes' Law

The motion of a body submerged in a fluid is determined by the forces acting upon the body. A particle will remain at rest with respect to fluid in which it is located until it is acted upon by some external force. This principle is Newton's first Law of Motion. It is further explained in his second law, which states that the acceleration upon a body caused by a force is proportional and parallel to the result of that force and inversely proportional to the mass of the body. A single isolated force is an impossiblity since any force acting upon a body is actually only one aspect of a mutual interaction between two bodies. A body exerting a force upon another body always encounters an equal and oppositely directed force exerted by the second body. This principle is Newton's third Law of Motion. The application of these laws upon a sphere of unit density falling in dry air is the basis for Stokes' Law.

Newton's first law is contained in his second law since if the force *(F)* acting upon a body is $F=0$, then the acceleration (a) of the body is $a=0$. In the absence of an applied force, the body will move at a constant velocity. This concept makes possible the calculation of the constant terminal or settling velocity of a body suspended in a fluid. If the magnitude of the forces acting upon the body and the size and shape of the body are known, its terminal velocity can be computed. A convenient system for testing the calculations used by Stokes was a sphere of unit density falling in dry air. The sphere can be physically defined as having an area

(Eq.9-20)

$$A_p = \frac{\pi D_p^{\,2}}{4}$$

where A_p = *sphere area projected on a plane normal to the fluid flow*
D_p = *sphere diameter*

(Eq.9-21)

and a mass
$$M_p = \frac{\varrho_p \, \pi (D_p)^3}{6}$$

where M_p = *mass of the sphere*
ϱ_p = *true sphere density*.

The discussion of streamline fluid flow around a body shows that a frictional drag exists on the body defined for a sphere

(Eq.9-22)
$$F_r = \left[\frac{\varrho u^2}{2}\right] A_p C$$

where
F_r = *drag friction*
C = *drag coefficient*
u = *relative velocity of the particle in the fluid*
ϱ = *density of fluid*.

The sphere will have a terminal velocity when the gravitational force acting on the body

(Eq.9-23)
$$F_g = g_L M_p \left[\frac{\varrho_p - \varrho}{\varrho_p}\right]$$

where
g_L = *local gravitational acceleration*
F_g = *gravitational force*

and the frictional forces are equal: $F_g = F_r$. The net force on the body equals zero.

(Eq.9-24)
$$F_g \downarrow \quad \uparrow F_r \qquad \text{Net Force} = 0$$

The terminal velocity (u_t) can be calculated:

(Eq.9-25)
$$u_t = \left[\frac{2 g_L M_p (\varrho_p - \varrho)}{\varrho \varrho_p A_p C}\right]^{1/2} = \left[\frac{4 g_L D_p (\varrho_p - \varrho)}{3 \varrho C}\right]^{1/2}$$

A mathematical proof by Stokes showed that when inertial terms in streamline fluid flow are negligible the frictional drag on a body submerged in the fluid can be expressed as

(Eq.9-26)
$$F_r' = 3\pi \, \mu \, u \, D_p$$

where

μ = *viscosity of the fluid*.

Substituting this expression into the original frictional drag equation the coefficient of drag (C) upon the body may be defined

$$(1)\ F_r = F_r'$$

$$(2)\ \frac{\varrho u^2 \pi D_p{}^2}{8} C = 3\pi\mu u D_p$$

$$(3)\ C = \frac{24\mu}{\varrho u D_p}.$$

Using the above definition of drag coefficient in the equation for terminal velocity and reducing all terms, the terminal velocity may be expressed:

(Eq.9-27) $$u_t = g_L\, D_p^2(\varrho_p - \varrho)/18\mu.$$

The conclusion that can be drawn from this complex proof is that a particle in a fluid will have a terminal or settling velocity when the net forces acting upon it are equal to zero. The velocity of the settling particle will be determined by the viscosity of the fluid and be proportional to the size and mass of the particle. These factors can make possible prediction of the physical properties proportional to the size and mass of the particle.

Cunningham "Slip" Factor and Brownian Movement

The calculations in Stokes' Law hold for unit density particles between 3-100μm in size. A particle smaller than 3μm has a higher terminal velocity than expected by Stokes' Law. Particles in this range are approaching the mean free path length of fluid molecules and experience less resistance than larger particles. A correction factor developed experimentally was determined by Cunningham to calculate the increased settling velocity of these particles.

The particles in this size range ($\leq 3\mu$m) are also subject to the effects of Brownian movement. The particle experiences random motion from collision with fluid molecules. This movement by collision is very important for correcting gravitational settling velocity for particles $\geq 0.1\mu\text{m} \leq 3\mu$m. The effect of Brownian movement upon particles $\leq 0.1\mu$m is much greater than gravitational settling velocity. Brownian movement is a diffusion property analogous to the diffusion properties of a gas. Particles subject to Brownian movement exert a partial pressure in the fluid proportional to their concentration.

Inertial Particle Sizing

The principles of isokinetic source sampling are founded upon the fluid dynamics in the preceding discussion. An isokinetic sample taken from a gas stream does not disturb the gas streamlines. It draws gas into the sampling nozzle with a force equal to the forces propelling the gas up the stack. The distribution of particles entering the sampling nozzle is theoretically the same as that existing in the stack. Isokinetic sampling does not exert excess external forces upon the particles in the gas stream; therefore, an unbiased sample is taken. If the sampling were done over isokinetically, external force would be exerted on particles in the gas. The gas streamlines would be drawn closer together, bringing a larger percentage of small particles into the sample. This analysis is based on particle inertia and fluid resistance to particle movement relative to the fluid.

The inertial particle sizing devices operate to yield the best data when an isokinetic sample enters the sample nozzle. The sample in the device contains a valid representative sample of the particles distributed in the gas stream. Particles of different size and mass are then separated by their inertia. The inertia of each particle is proportional to its size and mass. This particle inertial force acts against the resistive frictional forces of the surrounding fluid. The particle reaches its terminal or settling velocity when these forces are equal. The inertial particle sizing device creates a different fluid flow characteristic for various stages within the device by causing the streamlines to come closer together. Particles that have attained their settling velocity at a given stage in the sizing device do not follow the gas streamlines and move out of the gas to impact on a collection stage. The diagram illustrates the concept involved.

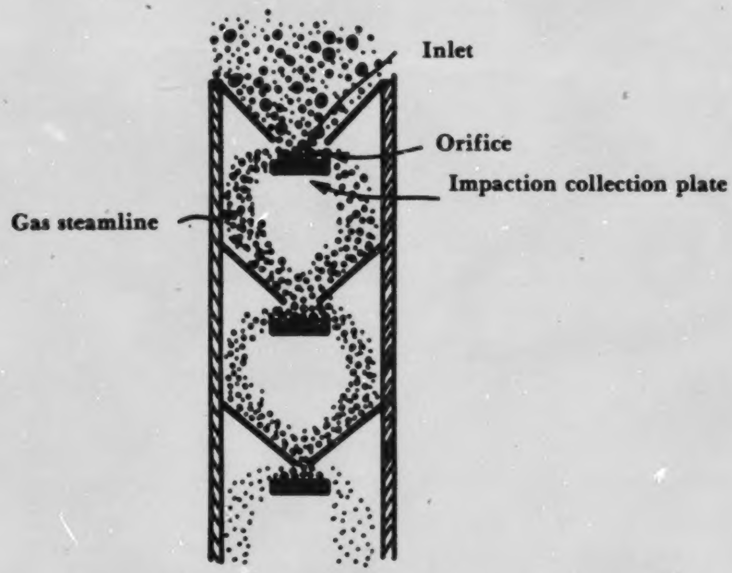


Figure 9-7. Inertial particle collector.

The particles have been separated based upon forces proportional to their size and mass. The device used must be calibrated with particles of known size, shape, and mass so the data for the unknown particles can be correlated. The most convenient method of calibration uses spherical particles of unit density dispersed in dry air at standard temperature. The shape and size of the unknown particles is not known directly; however, based on their behavior in the sizing device, an "effect diameter" is determined which is related to the calibration spheres. Particles of unknown shape sized in an inertial sizing device that correlates particle size to reference sphere calibration data are assigned an "aerodynamic diameter." This term is used since the particles have been sized based upon the similarities exhibited between the behavior of calibration spheres and the particle in a gas stream. The aerodynamic diameter is related to the particle geometric diameter, particle density, and shape in the expression:

(Eq.9-28)

$$d_a = K \frac{\varrho_p}{\varrho_o} d_g$$

where:

d_g = *geometric diameter*
ϱ_p = *particle density*
ϱ_o = *unit density* $(1\ g\ cm^{-3})$
K = *shape factor; for spheres* = 1.

This data, in conjunction with knowledge of the chemical composition of the particles, affords sufficient information for predicting particle physical properties.

The inertial particle sizing technique is a very useful method of assessing particle size; however, it is subject to some limitations and problems. The inertial technique for sizing particles is preferred since it can be used *in situ*, avoiding the sampling errors created by extractive systems. The *in situ* device is not subject to biases created by electrostatic and thermal gradients, particle agglomeration in the sample probe, or new particle formation at lower than stack temperature. It can, however, have smeared particle size cut-off points at the collection stage. This problem is related to the finite dimensions of the sizing device. The changing fluid velocity and viscosity effects the collection efficiency of each size stage.

A collection stage collects particles of which a percentage correspond to one size with others above or below this size cutoff. The particle size for a given stage is, therefore, generally termed a "fractionation size," which is a definition of the collection stage efficiency. The D_{50} for any stage is defined as the size of particles collected on each stage with at least 50% collection efficiency, for a given set of impactor conditions. The proper D_{50} for a collection stage can be maintained only if the particle sizing device is operated at a gas flow rate that does not produce fracturing or scouring of particles. If the sample gas flow rate is too high, particles can be broken upon impact with the collection stage or settled particles could be re-entrained into the gas stream. This would create significant errors in collection efficiency for the impact stage.

Alternate Sizing Methods

A number of other methods exist for sizing particles. The method chosen for a given sampling situation should be thoroughly evaluated in relation to the scope of the work. Several methods employ particle mass, size, and shape in a manner theoretically similar to the inertial sizer. Elutriation and sedimentation methods are extractive methods that are, in principle, very similar to the inertial impactor—they separate different size and mass particles based on terminal settling velocity. These are usually used in the laboratory. Another laboratory technique is the Bacho centrifugal separation. This device incorporates a radial gas stream of known tangential velocity to separate particles by size and mass. It, like the elutriation and sedimentation devices, is subject to the uncertainties and high repetition is necessary in determining particle size from a sample collected out of the original gas stream.

Microscopic analysis of particle sizing again requires high repetition to gain a statistically representative evaluation of particle size. This technique requires that those particles analyzed under the microscope do not agglomerate or overlap.

Data Analysis

A variety of methods exist for presenting particle size data. The method selected for a particular situation will most likely be chosen based upon the type of sizing system used, convenience, and intended use of the data. The most common methods of presenting data are cumulative or frequency distribution curves. A frequency distribution curve plots the number or weight of an incremental size range against the average particle size of the given range. This is based upon the concept that physical laws control the formation of particulates in any system. Particles tend to form a preferential size for a given system which can be determined empirically. Particle size frequency distributions, therefore, approximate a probability relationship with a peak at a preferential size. The cumulative distribution is a plot of the fraction of the total number of particulates (or weight of particles) which have a diameter greater than or less than a given size plotted against the size. This is actually an integrated frequency distribution curve.

The majority of inertial impactor particle size data uses the D_{50} method of data reduction. The particles on a given stage are assumed to have a diameter equal to the calculated D_{50} for that stage. Once the D_{50} for each stage has been determined, the data can be simplified to yield a differential or cumulative plot of the particle size sampled.

The cumulative plot of particle distribution is clear and easy to understand. The weight of particulate collected for each stage is presented as a percent of the total particulate catch. The data is then plotted as percent versus diameter yielding a cumulative particle distribution curve. The method has a drawback in that a weighing error is propagated throughout the data. Good calibration of the sizing device greatly improves the data.

D. OPACITY MONITORING

Introduction

One of the more recent developments in the evaluation of source emissions has been in the use of the transmissometer or opacity monitor. A knowledge of the operation and type of information that may be obtained from these instruments is very important for both the stack sampler and the stack test observer. Several consulting firms are now using transmissometers during Method 5 tests to verify the stability of the source emissions during the testing period. Values of opacity may even be used to determine the mass emission rate if a prior correlation exists between the two for a given source. These techniques can be invaluable for checking the validity of the Method 5 data itself.

The term "transmissometer" comes from the word "transmittance." When light passes through a plume of smoke, some of it will be transmitted and will be able to be observed on the other side of the plume. Some of the light, however, will be scattered or absorbed by the particulate matter in the plume and will be lost to the observer. If light is not able to penetrate through the plume at all, the plume is said to be completely opaque, i.e., the "opacity" of the plume is 100%. Transmittance and opacity can be related in the following manner:

$$\%\ \text{Transmittance} = 100 - \%\ \text{Opacity}$$

Therefore, if a plume or object is 100% opaque, the transmittance of light through it is zero. If it is not opaque at all (zero % opacity), the transmittance of light will be 100%. Of course, a plume from a stationary source will generally not have either zero or 100% opacity, but some intermediate value. In the New Source Performance Standards, the opacity limits have been established for a number of stationary sources. The following sources are those required to continuously monitor their emissions and maintain them within the given standard:

	Opacity Limit
Fossil—Fuel Fired Steam Generators	20%
Petroleum Refineries (Catalytic Cracker)	30
Electric Arc Furnaces	15
Primary Copper, Lead, and Zinc Smelters	20
Kraft Pulp Mills (recovery furnace)	35

Continuous monitoring regulations for opacity were made to ensure that source control equipment is properly operated and maintained at all times. EPA does not consider the transmissometer to be an enforcement tool since the visible emissions observer (EPA Reference Method 9) is still used to enforce the source opacity standards. However, data from the transmissometer may be used as evidence of the opacity of an emission (see 42 FR 26205 5/23/77).

The Transmissometer

A transmissometer may be constructed in two ways, using either a single pass system (Figure 9-8) or a double pass system (Figure 9-9).

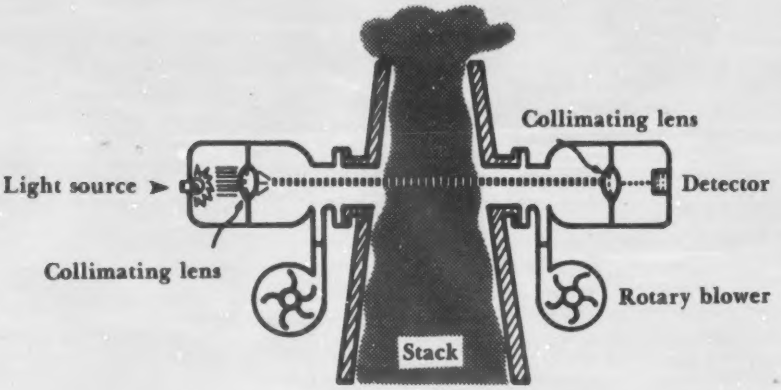

Collimating lens
Light source
Detector
Collimating lens
Rotary blower
Stack

Figure 9-8. Single-pass system.

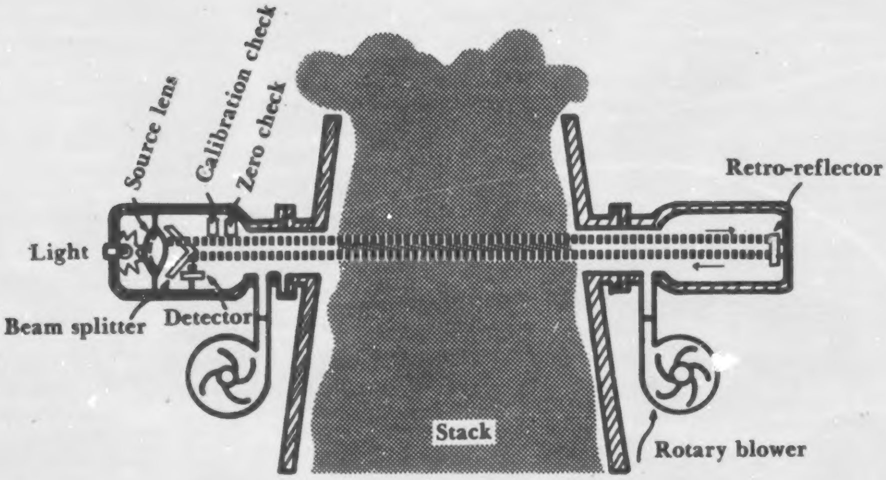

Source lens
Calibration check
Zero check
Retro-reflector
Light
Beam splitter
Detector
Stack
Rotary blower

Figure 9-9. Double-pass system.

In the single pass system, a lamp simply projects a beam of light across the stack or duct leading to the stack, and the amount of light transmitted through the flue gas is sensed by a detector. Instruments designed in this configuration can be made rather inexpensively; however, they often do not satisfy EPA criteria for system zero and calibration checks. The double pass system shown in Figure 9-9 houses both the light source and light detector in one unit. By reflecting the projected light from a mirror on the opposite side of the stack, systems can be easily designed to check all of the electronic circuitry, including the lamp and photodetector, as part of the operating procedure. Most transmissometer systems include some type of air purging system or blower to keep the optical windows clean. In the case of positive pressure stacks ($P_S > 0$), the purging system should be efficient or the windows will become dirty, leading to spuriously high readings.

In contrast to ambient air continous monitoring instrumentation, EPA does not "approve" specific manufacturer models. Since most stationary sources have unique monitoring problems, EPA has established the "Performance Specification Test" as a procedure for assuring that the instrument will operate properly once mounted in a stack or duct. In addition, the transmissometer itself must satisfy several "design specifications." Meeting the design specifications and passing the Performance Specification Test constitute approval of the specific opacity monitoring installation.

Design Specifications

There are essentially seven design criteria that must be met by an opacity monitor. These are as follows:

- Spectral Response—The system must project a beam of light with the wavelength of maximum sensitivity lying between 500 and 600 nm. Also, no more than 10% of this peak response can be outside of the range of 400 to 700 nm.
- Angle of Projection—The angle of the light cone emitted from the system is limited to 5 degrees.
- Angle of View—The angle of the cone of observation of the photodetector assembly is limited to 5 degrees.
- Calibration Error—Using neutral density calibration filters, the instrument is limited to an error of 3% opacity.
- Response Time—The time interval required to go from an opacity value of zero to 95% of the value of a step change in opacity is limited to 10 seconds.
- Sampling—The monitoring system is required to complete a minimum of one measuring cycle every 10 seconds and one data recording cycle every 6 minutes.
- System Operation Check—The monitor system is to include a means of checking the "active" elements of the system in the zero and calibration procedures.

Before purchasing an opacity monitoring system, the instrument specifications should be carefuly checked to see if the monitor satisfies these minimum requirements. Failure to do so may mean that the monitor will not be accepted by EPA for application as a continuous monitor of source emissions.

There are several reasons for establishing these design specifications. The most important one is that there is no widely available independent method of checking the opacity. Instead, it is assumed that if the system is designed correctly and can be checked with filters for accuracy, it should be able to give correct flue gas opacity readings. The rationale behind each of these specifications follows

Spectral Response

The transmissometer is required to project a beam of light in the "photopic" region — that region of the electromagnetic spectrum to which the human eye is sensitive (Figure 9-10).

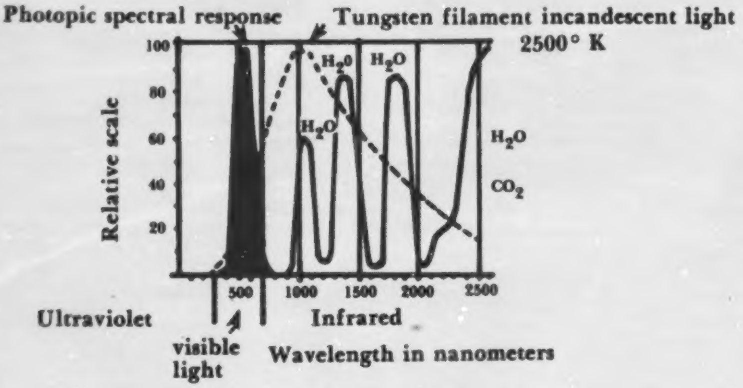


Figure 9-10. Photopic region.

There are three reasons for specifying this region:

- It was originally hoped to correlate the opacity readings of the transmissometer with those of a visible emissions observer performing EPA Method 9. If the transmissometer does project light in this region, the readings usually will be comparable. However, background light contrast, acid aerosol formation, and other problems may cause the readings by visible emissions observer to differ from the instrument readings.
- Water and carbon dioxide absorb light at wavelengths higher than 700 nm. If the transmissometer projected light in this region (as some earlier systems did), any water vapor or carbon dioxide in the flue gas would take away some of the light energy by absorption processes and a high opacity reading would result (see absorption regions in Figure 9-10. Since this would unduly penalize the operator (of a fossil fuel—fired boiler, for example) filters or special optics are required to limit the spectral response of the transmissometer.
- Small particles less than 0.5 micrometers in size will scatter light more effectively if the light has a wavelength in the region of 550 nm (Figure 9-11).

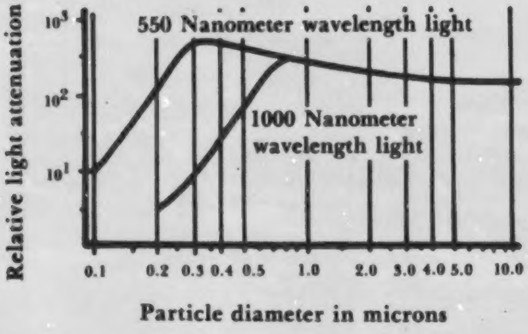


Figure 9-11. Particle size effects.

Since, with the application of control devices to industrial sources, particles tend to be small, light of short wavelength is required to detect them.

Angle of Projection

The ideal transmissometer would have a very thinly collimated, laser sharp beam projected across the stack. When a beam diverges, particles outside of the transmissometer path will absorb or scatter the light and light energy would be effectively lost outside of the path. This would appear as higher opacity readings. Because it is expensive to construct sharply collimated instruments, specifications have been given to limit beam divergence to 5 degrees, as shown in Figure 9-12.

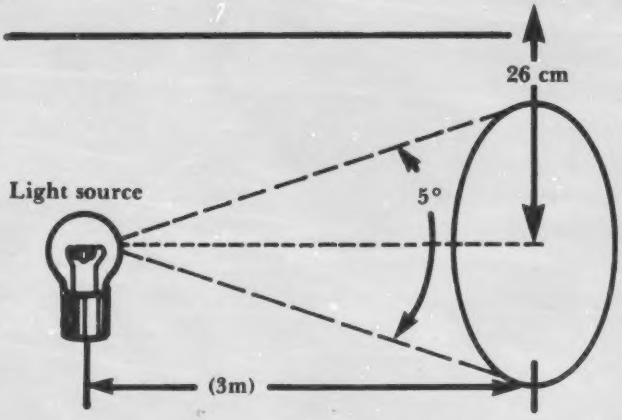


Figure 9-12. Angle of projection.

The procedure for checking the angle of projection is to draw an arc with a 3 meter radius, then measure the light intensity at 5 cm intervals for 26 cm on both sides of the center line.

Angle of View

The reason for specifying the angle of view of the detector assembly is similar to that for the projection angle specification. In this case, if the angle of view was too great, the detector might possibly pick up light outside of the transmissometer light path. It would therefore "see" more light energy than it should and the transmissometer readings would be lower than true (Figure 9-13).

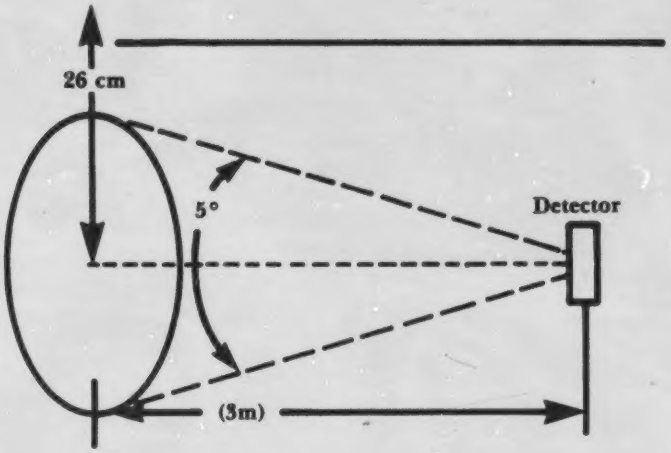


Figure 9-13. Angle of view.

The angle of view may be checked by using a small nondirectional light source to see where, on an arc of 3 meter radius, a signal will appear. Generally, however, the projection and detection angles are determined by the instrument manufacturer.

Calibration Error

Transmissometers are calibrated with neutral density filters corresponding to a given percent opacity. The calibration error test is the closest possible procedure to checking the accuracy of the instrument. Consequently, before an instrument is placed on a duct or stack, the instrument response to calibration filters is required to be within 3 percent of the predetermined filter values.

System Response Time Test

Since a transmissometer system is required by the regulations to measure opacity every 10 seconds, a satisfactory system must be able to obtain a value for opacity within this time period. An approvable transmissometer would have to reach 95% of a calibration filter value within 10 seconds after it was slipped into the light path to satisfy this design specification.

Sampling Criteria

EPA regulations specify that an approvable transmissometer must be able to complete a minimum of one measuring cycle every 10 seconds (40CFR60.13e). Also, some provision must be made in the monitoring *system* to record an averaged reading over a minimum of 24 data points every 6 minutes.

These specifications were established so that the opacity monitor would provide information corresponding to (a) the behavior of the particulate control equipment and (b) the data obtained by the visible emissions observer (EPA Method 9 requires the reading of 24 plumes at 15 second intervals).

System Operation Check

The system operation check often has not been recognized by instrument vendors as one of the design criteria for transmissometer systems. In fact, there is some question whether several of the currently marketed opacity monitors could be approved under this specification. In 40CFR60.13e3, it is stated:

> "...procedures shall provide a system check of the analyzer internal optical surfaces and all electronic circuitry including the lamp and photodetector assembly."

This means that when calibrating or zeroing the instrument, the lamp or photodetector used should be the same as that used in measuring the flue gas opacity. For this reason, most single-pass opacity monitors would not be acceptable under EPA design specifications, since a zero reading would not be obtainable unless the stack was shut down.

Installation Specifications

After a transmissometer that meets EPA design criteria has been selected by the source operator, the instrument must be installed and checked for proper operation on the source itself. There are several points that must be considered when installing a transmissometer:

1. The transmissometer must be located across a section of duct or stack that will provide a *representative* measurement of the actual flue gas opacity.
2. The transmissometer must be downstream from the particulate control equipment and as far away as possible from bends and obstructions.
3. The transmissometer located in a duct or stack following a bend must be installed in the *plane of the bend.*
4. The transmissometer should be installed in an accessible location.

5. The source operator may be required to demonstrate that the monitor is obtaining representative opacity values at its installed location.

It was intended that the transmissometer measure the actual flue gas opacity or "an optical volume *representative* of the particulate matter flow through the duct or stack." Figure 9-14 shows some of the problems in particulate matter flow distribution which might occur in an exhaust system.

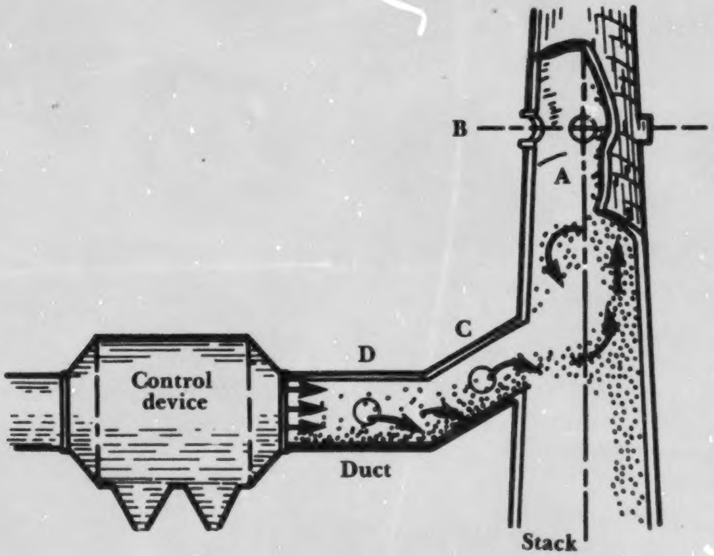


Figure 9-14. Transmissometer siting.

Particulate matter may settle in ducts or stratify in the flue gas stream depending upon the construction of the exhaust system. In Figure 9-14 the "plane of the bend" is that plane formed by the stack and the duct (in this case, the plane of the paper). If one were to locate a transmissometer perpendicular to this plane, such as at point A, a large portion of the particulate matter would not be seen by the inlet breech. A transmissometer located at B would be in the plane of the bend and would be sensing a cross-section of the total particulate flow. Location C would not be appropriate for an opacity monitor because the monitor would not be in the plane formed by the horizontal duct and the breeching duct. A monitor at location C also would not satisfy criteria 1 or 2 since settling or particulate matter might not provide a representative sample, in addition the location is close to two bends in the exhaust system. Location D would be one of the best points for monitoring. Here, the transmissometer would be most *accessible* and might be more carefully maintained than if located at B. Location D follows the control device and does not follow a bend. The only problem that might arise is the settling of particulate matter in the duct and possible reentrainment to give nonrepresentative opacity readings. An examination of the opacity profile over the width of the duct might be necessary to place the monitor at this point. Proper monitor siting is very important to the source operator since an inappropriate choice for the location of a monitor may cause measurement problems and entail expense, particularly if re-siting is necessary.

The Performance Specification Test

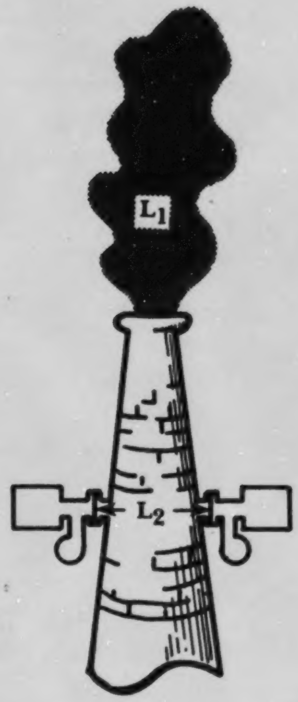
Before an opacity monitoring system can be used for EPA reporting requirements, it must undergo the Performance Specification Test. Since most sources differ in operational design and construction, a given monitor might perform well at one source but produce unacceptable data at another. Differences in location, particulate stratification, vibration, temperature, and other factors influence the requirement that the opacity monitor be shown to operate at the location for which it was intended. Design specifications are not sufficient for approval (in contrast to ambient air monitors); the performance test must also be performed.

The Performance Specification Test for opacity monitors requires that the instrument undergo a 1-week conditioning period and a 1-week operational test period. In the conditioning period, the monitor is merely turned on and run in a normal manner. This is essentially a "burn-in" period for the new instrument, and it is hoped that problems that might be expected for a new device will appear during this time. In the operational test period, the monitor is run for 1-week without any corrective maintenance, repair, or replacement of parts other than that required as normal operating procedure. During this period, 24-hour zero and calibration drift characteristics are determined. If the instrument is poorly designed or is poorly mounted, these problems should become evident from the drift data, and corrective action would have to be taken. The only actual data necessary in the performance test is that for zero and calibration drift. No relative accuracy test is taken since there is no EPA reference method that gives an appropriate "true value" for the opacity. (Since the EPA Method 9 visible emissions observer trains on a smoke generator calibrated with a transmissometer, this method could not give an independent opacity value.)

Data Reporting Requirements

After an opacity monitoring system has passed the Performance Specification Test, it may be used to monitor source emissions. New sources required to monitor opacity must report excess emissions on a quarterly basis. Since opacity standards are based on the opacity of the plume at the stack exit, the in-stack transmissometer data must be corrected to the stack exit pathlength using the relationship shown in Figure 9-15.

L_1 = Emission outlet pathlength
L_2 = Monitor pathlength
O_1 = Emission opacity
O_2 = Monitor opacity



$$O_1 = 1 - (1 - O_2)^{\frac{L_1}{L_2}}$$

Figure 9-15. Relation betwen emission opacity and monitor opacity.

The transmissometer system must be able to record the average of at least 24 equally-spaced opacity readings taken over a 6 minute period. Any readings in excess of the applicable standard (e.g., 20% opacity for a coal-fired boiler) must be reported. Also, a report of equipment malfunctions or modifications must be made. Although the recorded data does not have to be reported to EPA unless excess emissions occurred, the data must be retained for a minimum of 2 years.

Opacity Monitor Applications

The uses of opacity monitors extend beyond merely satisfying EPA requirements for installing such a system. Transmissometers have been used as combustion efficiency indicators, broken bag detectors, and as process monitors during EPA Method 5 tests. Some of these specific applications are:

- Installation to satisfy EPA continuous opacity monitoring requirements,
- Installation for process performance data—maintenance and repair indications, process improvement,
- Installation for control equipment operation—ESP tuning, broken bag detection,
- Correlation with particulate concentration,
- Maintenance of a continuous emissions record.

The primary impetus for installing opacity monitors has been, of course, to satisfy the EPA regulations contained in the New Source Performance Standards. (Sources presently required to continuously monitor opacity were given in the beginning of this chapter.) As previously stated, the application of monitoring instrumentation to stationary sources is intended to provide a continuous check on the operation of the air pollution control equipment. The source operator, however, can use the continuous monitoring data to optimize the operation of his process and control equipment. For example, in a fossil fuel-fired boiler, improper combustion conditions may lead to the production of unburned carbon and increased particulate matter. This might be caused by a blocked burner nozzle, a fouled stoker, or an incorrect fuel-air mixture ratio. If not enough excess air is added to the fuel in a coal or oil-fired boiler to give proper combustion, an opacity monitor would be able to detect an increase in the flue gas opacity, and corrective action could be taken (Note: a continuous CO monitor would also be useful in this respect). The optimization of combustion efficiency, reduction of carbon build-up on boiler tubes, and warning of process malfunctions are all benefits for the source operation.

Opacity monitors have been used in bag house and electrostatic precipitator applications. The breaking of a filter in a bag house will increase the opacity level of an exhaust gas and could be detected by an inexpensive single-pass transmissometer. Several companies currently market instruments for this purpose. Transmissometers have also been used to "tune" the rapping systems of electrostatic precipitators. By choosing the optimum rapping cycle of the precipitator collection plates as a function of smoke opacity, precipitator operating costs can be reduced and the emission standard met more easily. The application of transmissometers after wet scrubbing control equipment has met with some difficulty because of the presence of entrained water (water droplets) in the flue gas stream. These water droplets will scatter light and give a high opacity reading. To adequately monitor the particulate removal characteristics of a scrubber, the flue gas might have to be reheated to evaporate the droplets. The utility of the transmissometer in monitoring the proper operation of particulate control equipment was one of the primary reasons for the establishment of the EPA continuous monitoring regulations. It was felt that once a source had spent the money to put on a control device, there should be some way that both the source operator and environmental agency personnel could be assured that the system would operate in a satisfactory monitor; the transmissometer provides this assurance.

The extraction of a particulate sample from a flue gas stream for analysis has been the method the Environmental Protection Agency has used to check compliance to emission standards. It has been hoped for some time that the data obtained from an opacity monitor could be correlated with that obtained from the extractive method, EPA Method 5. This can be done, but only if two important considerations are kept in mind: (a) the particle characteristics must remain the same, and (b) the source operating characteristics must not change. Figures 9-16 and 9-17 show examples of correlations that have been made for a coal-fired boiler and a cement kiln.

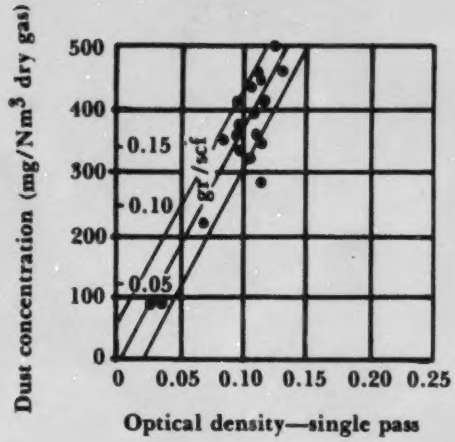


Figure 9-16. Bituminous coal fired boiler emissions.

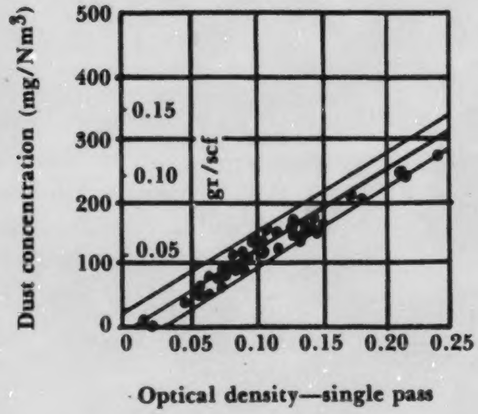


Figure 9-17. Cement kiln emissions.

Here, the particulate concentration is given as a function of the optical density. Optical density, O.D., is related to opacity in the following manner

(Eq.9-29) $$O.D. = \log_{10} \frac{1}{1 - Opacity} .$$

This is a very useful expression since by considering the properties of particulate scattering and absorption, a linear relationship between particulate concentration and optical density results. The Beer-Bougert Law for the transmittance of light through an aerosol states that

(Eq.9-30) $$T = e - naql \qquad or \qquad (1 - O) = e - naql$$

where

T = *transmittance*
n = *number concentration of particles*
a = *projected area of the particles*
q = *particle extinction coefficient*
l = *light path through the aerosol*
O = *opacity*

If the logarithm is taken of both sides, we have

$$\log\ (1-O) = -0.434naql$$

where 0.434 is conversion for $\log_{10}$

and

$$O.D. = \log \frac{1}{(1-O)} = Kcl$$

where K is a constant describing the characteristics of the particle scattering and c is the concentration (being proportional to n).

This states that O.D. = Kcl, or that the optical density is proportional to the particulate concentration. This is seen to be true from Figures 9-16 and 9-17. For this relationship to hold, the particle characteristics must remain constant. Generally, graphs like those given in Figures 9-16 and 9-17 are obtained by conducting a number of EPA Method 5 tests along with an operating transmissometer. The correlation between Method 5 and the transmissometer readings can be better than 10%.

Once such a relationship is made between opacity readings and particulate concentration, a stack tester could check his data in correspondence with those readings. As more data becomes available from different sources under different conditions, it is hoped that a library of such correlations can be made.

The basic use of an opacity monitoring system is for obtaining a continuous record. The stack tester, for the short term, can use transmissometer data to see if soot-blowing occurred during the period of the test or if any other conditions occurred that might give anomalous stack test results. For the long term, the continuous record can be used by the source operator to check the functioning of the control system or to note long term improvement or degradation of performance. Air pollution agency personnel can use such continuous data as evidence in compliance cases although as yet this type of data cannot be used directly to enforce standards. The continuous record, can however, tell the enforcement officer if there is a history of noncompliance or if a control device is not operating properly.

The transmissometer is a useful tool both for source operators and air pollution agency personnel. Through proper training and care of the instrument itself, valuable process formation and emissions data can be obtained.

Appendixes

A. Bibliography
B. Suggested References
C. Derivation of Equations
D. Concentration Correction Equations
E. International Metric System
F. Conversion Tables
G. Constants and Useful Information

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APPENDIX C. DERIVATION OF EQUATIONS

DERIVATION OF THE PITOT TUBE EQUATION

The pitot tube (Standard or Stausscheibe (S) Type) is used to measure the velocity of a gas. The pitot is actually a pressure sensing device that allows the determination of the gas stream velocity based upon the total system energy. Figure C-1 illustrates the fluid flow around a Standard Type pitot tube submerged in a gas stream.

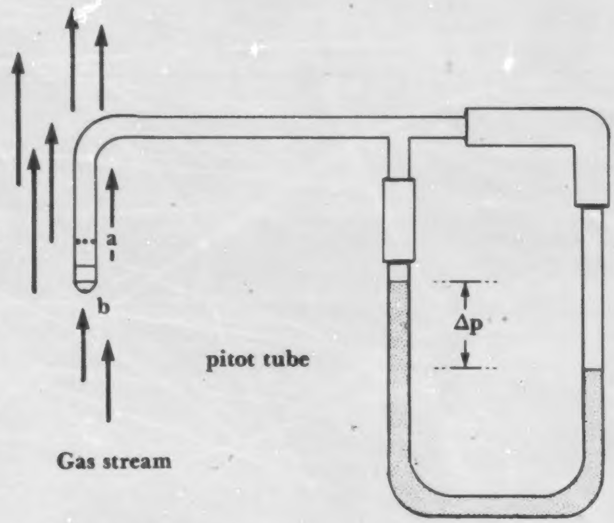


Figure C-1. Fluid flow around a Standard Type pitot tube.

Applying Bernoulli's equation to points "a" and "b" we may describe the system:

Eq. C-1

$$P_b + \tfrac{1}{2}\varrho v^2 + \varrho g y_1 = P_a + \tfrac{1}{2}\varrho v^2 + \varrho g y_2$$

where:

P_b = *full ram gas pressure at point b*
P_a = *free-stream gas pressure at point a – static pressure*
ϱ = *gas density*
g = *acceleration of gravity*
y = *some elevation above a reference level, which in this case is negligible, therefore,* $y_1 \cong y_2 \cong o$
v = *gas velocity*

Since $y_1 \cong y_2 \cong 0$ Equation C-1 may be written:

Eq. C-2 $$P_b + \tfrac{1}{2}\varrho v^2 = P_a + \tfrac{1}{2}\varrho v^2$$

At point b, the gas molecules stagnate, giving up their kinetic energy. The gas velocity at b is zero ($v = 0$) and Equation C-2 becomes:

Eq. C-3 $$P_b = P_a + \tfrac{1}{2}\varrho v^2$$

The kinetic energy of the gas molecules at b has been used to perform work on the manometer fluid changing the height of the column (Δp). The knowledge that the total energy in the system is conserved allows this derivation to proceed based on a description of pressure terms in the system. The pressures in the system are balanced when:

Eq. C-4 $$P_b = P_a + \varrho' g(\Delta p)$$

where:

ϱ' = *density of the manometer fluid*
Δp = *change in height of the manometer column*

The full ram pressure is equal to the sum of the system static pressure and the pressure of the manometer column. Rearranging terms in equations C-3 and C-4 we see:

Eq. C-5 $$\tfrac{1}{2}\varrho v^2 = \varrho' g(\Delta p)$$

and

Eq. C-6 $$v = \sqrt{\frac{2\varrho' g \Delta p}{\varrho}}$$

which describes the calculation of the gas velocity of an ideal gas in a system free of frictional energy losses.

The gas density may be described for a given gas of unknown density by using the ideal gas law. The gas density is defined:

Eq. C-7 $$\varrho = \frac{mass}{volume}$$

We know from the ideal gas law that:

Eq. C-8 $$P_s V = \frac{m}{M_s} R T_s$$

where:

P_s = absolute pressure
V = volume
m = mass of the gas
M_s = molecular weight of the gas
R = a constant
T_s = absolute gas temperature

Rearranging terms in equation C-8:

$$\frac{m}{V} = \frac{M_s P_s}{R T_s}$$

Then substituting in equations C-7 and C-6:

Eq. C-9

$$v = \sqrt{\frac{2\varrho' g \Delta p R T_s}{M_s P_s}}$$

By using the following values in equation C-9 we can calculate a constant (K_p):

Eq. C-10

$$\varrho'_{H_2O} = 62.428 \text{ lb/ft}^3$$

$$g = 32.174\ ft/sec^2$$

$$R = 21.83\ \frac{inches\ Hg - ft^3}{lb - mole - {}^\circ R}$$

$$12\ inches\ _{H_2O} = 1\ ft$$

$$K_p = \sqrt{\frac{2(62.428)(32.174)\ (21.83)}{12}}$$

$$= 85.486\ ft/sec \sqrt{\frac{(lb/lb - mole)\ (inches\ Hg)}{{}^\circ R - inches\ H_2O}}$$

$$v = K_p \sqrt{\frac{T_s \Delta p}{M_s P_s}}$$

The final term in our equation must account for the effect of friction and the resultant turbulence in our system. A properly constructed standard pitot tube will not be measurably influenced by frictional effects. It may be assigned a coefficient of friction ($C_{p_{std}}$) of units. Any other pitot tube would have to be corrected for the effects of turbulence about the tube. If we include $C_{p_{std}}$ in our velocity equation we have:

Eq. C-11 $$V = K_p C_{p_{std}} \sqrt{\frac{\Delta p T_s}{P_s M_s}}$$

The gas velocity calculated using a standard pitot tube with $C_{p(std)}$ will be equal to the velocity measured with an "S" type pitot tube if we know the $C_{p(s)}$ for the "S" type pitot. This may be written:

$$K_p C_{p(std)} \sqrt{\frac{\Delta p_{std} T_s}{P_s M_s}} = K_p C_{p(s)} \sqrt{\frac{\Delta p_{(s)} T_s}{P_s M_s}}$$

Solving for $C_{p(s)}$ we get an expression that allows us to compare the "S" type pitot tube to a standard pitot tube with a known coefficient of friction:

Eq. C-12 $$C_{p(s)} = C_{p(std)} \sqrt{\frac{\Delta p_{std}}{\Delta p_s}}$$

We may now use any pitot tube to measure gas velocity once we know its $C_{p(s)}$.

DERIVATION OF ISOKINETIC RATE EQUATION

Introduction

Orifice meter setting ΔH actually correlates many factors to produce a gas velocity at the sampling nozzle equal to the velocity of the approaching gas stream.

Developing the derivation will depend on the following relationships:

- Velocity of the stack (v_s) equals the velocity of the gas entering the nozzle (v_n) at isokinetic conditions. From the pitot tube equation

Eq. C-13 $$v_s = K_p C_p \sqrt{\frac{T_s \Delta p}{P_s M_s}}$$

- The volumetric flow rate at the nozzle tip (Q_n) equals the nozzle cross-sectional area (A_n) times the gas velocity at the nozzle (v_n)

Eq. C-14 $$Q_n = A_n v_n = A_n v_s$$

- The volumetric flow rate at the meter Q_m is related to Q_n by the ideal gas law. Assuming that the mass flow rate does not change

Eq. C-15 $$Q_n = A_n v_s = Q_m \frac{P_m}{P_s} \frac{T_s}{T_m}$$

- Correcting the mass flow rate at the meter for the condensation of water vapor

Eq. C-16

$$Q_n = Q_m \frac{P_m}{P_s} \frac{T_s}{T_m} \left(\frac{1 - B_{wm}}{1 - B_{ws}} \right)$$

- The flow rate at the meter is given

Eq. 17

$$Q_m = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}}$$

Derivation

Equations will be solved to give ΔH—the pressure differential across the orifice meter for a given Δp in the stack.

From equation C-16

Eq. C-18

$$Q_n = Q_m \left(\frac{P_m T_s}{P_s T_m} \right) \left(\frac{1 - B_{wm}}{1 - B_{ws}} \right)$$

Substituting for Q_m from Equation C-17

Eq. C-19

$$Q_n = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \frac{P_m}{P_s} \frac{T_s}{T_m} \left(\frac{1 - B_{wm}}{1 - B_{ws}} \right)$$

Replacing $A_n v_s$ for Q_n from Equation C-14

Eq. C-20

$$A_n v_s = K_m \sqrt{\frac{T_m \Delta H}{P_m M_m}} \frac{P_m}{P_s} \frac{T_s}{T_m} \left(\frac{1 - B_{wm}}{1 - B_{ws}} \right)$$

Substituting $A_n = \dfrac{\pi {D_n}^2}{4}$ and $v_s = K_p C_p \sqrt{\dfrac{T_s \Delta p}{P_s M_s}}$

then squaring both sides of the equation

Eq. C-21

$$\left(\frac{\pi {D_n}^2}{4} \right)^2 {K_p}^2 {C_p}^2 \left(\frac{T_s \Delta p}{P_s M_s} \right) = {K_m}^2 \left(\frac{T_m \Delta H}{P_m M_m} \right) \frac{{P_m}^2}{{P_s}^2} \frac{{T_s}^2}{{T_m}^2} \left(\frac{1 - B_{wm}}{1 - B_{ws}} \right)^2$$

Solving for ΔH

Eq. C-22 $$\Delta H = D_n{}^4 \left(\frac{\pi K_p C_p}{4K_m}\right)^2 \left(\frac{1-B_{ws}}{1-B_{wm}}\right)^2 \frac{M_m}{M_s} \; \frac{T_m}{T_s} \; \frac{P_s}{P_m} \left[\Delta p\right]$$

Substituting $M_m = M_d(1 - B_{wm}) + 18B_{wm}$ and $M_s = M_d(1 - B_{ws}) + 18B_{ws}$

Eq. C-23

$$\Delta H = D_n{}^4 \left(\frac{\pi K_p C_p}{4K_m}\right)^2 \frac{(1-B_{ws})^2}{(1-B_{wm})^2} \left[\frac{M_d(1-B_{wm})+18B_{wm}}{M_d(1-B_{ws})+18B_{ws}}\right] \frac{T_m}{T_s} \; \frac{P_s}{P_m} \left[\Delta p\right]$$

or

$$\Delta H = \left[846.72 \; D_n^4 \; \Delta H_@ \; c_p^2 (1-B_{ws})^2 \; \frac{M_d \; T_m \; P_s}{M_s \; T_s \; P_m}\right] \Delta p$$

when assuming

$$B_{wm} = 0$$

$$\Delta H_@ = \frac{.9244}{K_m^2}$$

$$K_p = 85.49$$

DERIVATION OF THE ISOKINETIC VARIATION EQUATIONS

The term isokinetic sampling is defined as an equal or uniform sampling of gas in motion. This is accomplished when the fluid streamlines of the stack gas are not disturbed. The EPA Method 5 source sampling system is designed to extract, from a stack, an isokinetic gas and particulate sample. A 100% isokinetic source sample is taken when the gas velocity into the sampling nozzle (v_n) is equal to the velocity of the approaching gas stream (v_s)

Eq. C-24 $$\%\ \textit{isokinetic variation} = \frac{v_n}{v_s} \times 100$$

The stack gas velocity (v_s) is measured using a pitot tube to determine the stack gas impact and static pressures. Bernoulli's theorem applied for the pitot tube and solved for gas velocity gives the expression

Eq. C-25 $$v_s = K_p C_p \sqrt{\frac{T_s \; \Delta p}{P_s M_s}}$$

The velocity of the gas entering the source sampling nozzle is determined from the principles in the equation of continuity. Solving the equation of continuity for velocity at the nozzle, we may express the relationship

Eq. C-26 $$V_n = \frac{Q_n}{A_n}$$

The nozzle cross-sectional area (A_n) is measured directly. The volumetric flow rate of gas at nozzle conditions (Q_n) is determined by correcting the dry gas volume metered by the orifice back to stack conditions. The water vapor condensed in the impingers must be included in this correction. Liquid water collected is converted to vapor phase volume at stack conditions to obtain the volume sampled at the nozzle.

The liquid water condensed (V_{lc}) multiplied by the water density (ϱ_{H_2O}) gives the mass of water collected in the impingers

Eq. C-27

$$(V_{lc})\ (\varrho_{H_2O}) = m$$

In the ideal gas law

Eq. C-28

$$PV = \frac{m}{M_{H_2O}} RT$$

Solving the expression for volume

$$V = \frac{T}{P}\ \frac{mR}{M_{H_2O}}$$

The volume at stack conditions is then

$$(V_{lc})\ (\varrho_{H_2O}) = m$$

$$V_{sw} = \frac{T_s}{P_s}\ \frac{mR}{M}$$

$$V_{sw} = \frac{T_s}{Ps}\ \frac{(V_{lc})\ (\varrho_{H_2O})R}{M_{H_2O}}$$

$$V_{sw} = \frac{Ts}{Ps}\ (V_{lc})K$$

The gas volume metered at the orifice is corrected for orifice pressure and temperature then added to V_{sw}. This total is corrected to stack conditions over the sampling time period to give Q_n

Eq. C-29

$$Q_n = \frac{\frac{Ts}{Ps}\left[(V_{lc})\ (K) + (V_m/T_m)(P_b + \frac{\Delta H}{13.6})\right]}{\theta}$$

Then, since

$$\%I = \frac{v_n}{v_s} \times 100$$

and

$$v_n = \frac{Q_n}{A_n}$$

we have by substitution

$$\%I = \frac{\frac{T_s}{P_s}\left[V_{lc}(K) + V_m/T_m(P_b + \frac{\Delta H}{13.6})\right]}{\theta A_n V_s}$$

Rearranging terms and including a correction for converting minutes to seconds to cancel out dimensions, we obtain the expression in the *Federal Register* for isokinetic variation

Eq. C-30 $$\%I = 100 \times \frac{Ts\left[V_{lc}K + V_m/T_m\left(P_b + \frac{\Delta H}{13.6}\right)\right]}{60\theta A_n V_s P_s}$$

with the constant (K) equal to

$$K = 0.003454 \ \frac{mmHg - m^3}{ml - {}^\circ K} \qquad (metric)$$

and

$$K = 0.002669 \ \frac{\text{in. Hg-ft}^3}{ml - {}^\circ R} \qquad (English\ Units)$$

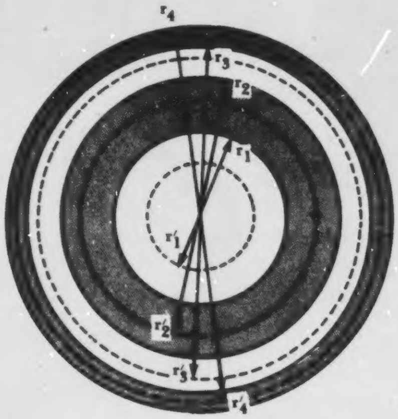
DERIVATION OF CONCENTRIC EQUAL AREAS OF A CIRCULAR DUCT

Traverse points are located at the centroid of an equal area in a circular duct.

A traverse point is thus a distance from the center of the duct—a radius of a concentric equal area.

The distance or radius (r_j') for a traverse point (j) for any circular duct having (N) equal areas may be determined in the following manner:

We know that $\pi r^2 = area\ of\ a\ circle$



From the diagram we see:

Eq. C-31 $$\pi r_2^2 - \pi r_1^2 = \pi r_1^2$$

which simplifies to:

Eq. C-32 $$r_1^2 = \frac{r_2^2}{2}$$

Dividing these again into equal areas

Eq. C-33 $$r_2'^2 - r_1^2 = r_2^2 - r_2'^2$$

Eq. C-34 $$r_3'^2 - r_2^2 = r_3^2 - r_3'^2$$

Solving Equations C-33 and C-34 and expressing in generalized form, the locus of points r_j' separating any area *(j)* into two equal areas is:

Eq. C-35 $$r_j'^2 = \frac{r_j^2 + r^2_{j-1}}{2}$$

Dividing the duct of radius *R* into *N* equal areas we find:

Eq. C-36 $$\frac{\pi R^2}{N} = \pi \left(r_j^2 - r_{j-1}^2 \right)$$

$$r_{j-1}^2 = r_j^2 - \frac{R^2}{N}$$

Substituting for r_{j-1}^2 in Equation C-35

$$r_j'^2 = \frac{r_j^2 + r_j^2 - \frac{R^2}{\mathrm{N}}}{2}$$

$$= \frac{2\, r_j^2 - \frac{R^2}{\mathrm{N}}}{2}$$

$$= \frac{2Nr_j^2 - R^2}{2N}$$

Solving Equation C-34 for r_j':

Eq. C-37

$$r_j'^2 = \frac{R^2\left(\frac{2Nr_j^2}{R^2} - 1\right)}{2N}$$

$$r_j' = R\sqrt{\frac{2N(r_j^2/R^2) - 1}{2N}}$$

The duct was divided into N equal areas each defined by a radius r_1, r_2, r_3, r_4, ...r_j. r_j' is the locus of points dividing each area into 2 equal areas. From the diagram, $N = 4$ and:

$$\frac{\pi r_1^2}{\pi R^2} = 1/4$$

$$\frac{\pi r_2^2}{\pi R^2} = 2/4$$

$$\frac{\pi r_3^2}{\pi R^2} = 3/4$$

$$\frac{\pi r_4^2}{\pi R^2} = 4/4$$

generalizing:

Eq. C-38

$$\frac{r_j^2}{R^2} = \frac{j}{N}$$

Substituting into equation C-31 and simplifying:

Eq. C-39

$$r_j' = R\sqrt{\frac{2N\frac{j}{N} - 1}{2N}}$$

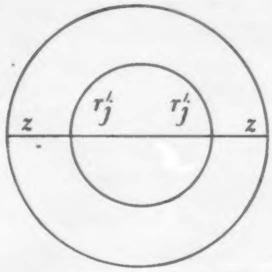
$$= R\sqrt{\frac{2j - 1}{2N}}$$

where: j = any locus of points dividing an equal area into 2 equal areas (i.e., traverse point at the centroid of an equal area) and N = number of equal areas.

The percent of the duct diameter (P) (the distance from the inside wall of the duct to a traverse point) is obtained for r'_j by the following method.

(Eq.C-40)

a.



From the diagram

$$2r'_j + 2z = \text{Diameter } D$$

$$z = \frac{D - 2r'_j}{2}$$

b. Percent of diameter $(P) = \frac{z}{D} \times 100$

Substituting from equations C-40 and C-39 and simplifying

$$P = \frac{(D - 2r'_j)100}{2} \div D$$

$$= \frac{50(D - 2r'_j)}{D}$$

$$P = \frac{50\left(D - 2R\sqrt{\frac{2j-1}{2N}}\right)}{D}$$

where
P = percent of diameter from inside duct wall to radius r'_j
N = total number of equal areas
j = specific area for which the location of points is calculated
j = 1, 2, 3, 4... from the center of duct outward.

DERIVATION OF THE EQUIVALENT DIAMETER EQUATION FOR ANY SHAPE DUCT

The equivalent diameter (E_D) for a duct is also defined as the hydraulic duct diameter (H_D). The hydraulic radius (R_H) for a duct transporting fluids is defined as the cross-sectional area of that part of the channel that is filled with fluid divided by the length of the wetted perimeter.

A stack gas will completely fill a duct and the entire duct perimeter will be wetted. Considering this situation for a circular duct we find

(Eq.C-41)

$$R_H = \frac{\pi\left(\frac{d}{2}\right)^2}{\pi d} = \frac{\frac{d^2}{4}}{d} = \frac{1}{4d}$$

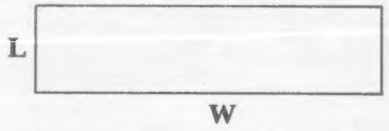
This illustrates that the hydraulic radius of a circular duct is one-fourth the duct diameter. The equivalent or hydraulic diameter for a noncircular pipe is 4 times the hydraulic radius

(Eq.C-42)

$$4R_H = H_D = E_D$$

The equivalent diameter for the rectangular duct illustrated would be:

(Eq.C-43)



$$4R^H = 4\ \frac{L \times W}{2L + 2W} = 2\ \frac{L \times W}{L + W} = E_D$$

which is the equation given in the Federal Register: this equation can be used for determining the equivalent diameter of any duct. Method I guidelines can then be applied.

DERIVATION OF THE EQUATIONS FOR MEASURING WATER VAPOR

Nomenclature

B_{ws} = proportion by volume of water vapor in a duct-gas at the sampling-point.

B'_w = proportion by volume of water vapor in a gas-mixture for saturated conditions.

e_a = water vapor pressure in a gas-mixture passing a wet-and dry-bulb thermometer assembly.

e_s = water vapor pressure in a gas-mixture at the sampling point.

e'_s = water vapor pressure in a gas-mixture for saturated conditions and dry-bulb temperature at the sampling-point.

e'_m = water vapor pressure for saturated conditions and meter temperature.

e'' = water vapor pressure at saturated conditions and wet-bulb temperature.

M_w = molecular weight of water (mass per mole)

m_{wc} = mass of water collected in the condenser.

P_a = absolute pressure at the wet-and dry-bulb temperature assembly.

P_s = absolute pressure of a duct-gas at the sampling point.

P_m = absolute pressure at the meter.
P_{mix} = absolute pressure of a gas-mixture.
R = universal gas constant.
T_m = absolute temperature at the meter.
$t_{dry(°C)}$ = dry-bulb temperature in °C.
$t_{dry(°F)}$ = dry-bulb temperature in °F.
$t_{wet(°C)}$ = dry-bulb temperature in °C.
$t_{wet(°F)}$ = wet-bulb temperature in °F.
V_m = volume of gas passed through the meter at meter conditions.
V_{wc} = volume of water vapor that condensed at the condenser referred to meter conditions.
V_{ws} = volume of water vapor extracted from the duct referred to meter conditions.
V_{wm} = volume of water vapor passed through the meter referred to meter conditions.
ϕ_o = relative humidity of the duct-gas.

Water Vapor Pressure and Proportion of Water Vapor by Volume in a Gas-Mixture

Saturated Conditions

Water vapor pressure

Water vapor pressures for saturated conditions are given in Figure C-2.

Proportion of water vapor

The proportion (by volume) of water vapor in a gas-mixture for saturated conditions given by

(Eq.C-44)
$$B'_w = \frac{e'}{P_{mix}} \qquad (1)$$

Non-Saturated Conditions

Wet- and dry-bulb method

a. Proportion of water vapor in a duct-gas.

If it is expected that the proportion by volume of water vapor in a duct-gas will be less than 15%, or that the dewpoint is less than 126°F, the wet- and dry-bulb temperature method may be used to determine water vapor pressure. Care must be taken that the flow past the wet bulb is 12 to 30 feet per second, and that temperature has reached equilibrium. It is essential that the dry-bulb, as well as the wet-bulb, be completely immersed in the gas, and that the cloth wick around the wet-bulb be clean, saturated with water, and tied tightly at all times. For the most accurate results, the two thermometers should be similar.

Wet Bulb Temp. Deg. F.	0	1	2	3	4	5	6	7	8	9
– – – 20	.0126	.0119	.0112	.0106	.0100	.0095	.0089	.0084	.0080	.0075
– – – 10	.0222	.0209	.0199	.0187	.0176	.0168	.0158	.0150	.0142	.0134
– – –	.0376	.0359	.0339	.0324	.0306	.0289	.0275	.0250	.0247	.0233
0	.0376	.0398	.0417	.0463	.0441	.0489	.0517	.0541	.0571	.0598
10	.0631	.0660	.0696	.0728	.0768	.0810	.0846	.0892	.0932	.0982
20	.1025	.1080	.1127	.1186	.1248	.1302	.1370	.1429	.1502	.1567
30	.1647	.1716	.1803	.1878	.1955	.2035	.2118	.2203	.2292	.2382
40	.2478	.2576	.2677	.2782	.2891	.3004	.3120	.3240	.3364	.3493
50	.3626	.3764	.3906	.4052	.4203	.4359	.4520	.4586	.4858	.5035
60	.5218	.5407	.5601	.5802	.6009	.6222	.6442	.6669	.6903	.7144
70	.7392	.7648	.7912	.8183	.8462	.8750	.9046	.9352	.9666	.9989
80	1.032	1.066	1.102	1.138	1.175	1.213	1.253	1.293	1.335	1.378
90	1.422	1.467	1.513	1.561	1.610	1.660	1.712	1.765	1.819	1.875
100	1.932	1.991	2.052	2.114	2.178	2.243	2.310	2.379	2.449	2.521
110	2.596	2.672	2.749	2.829	2.911	2.995	3.081	3.169	3.259	3.351
120	3.446	3.543	3.642	3.744	3.848	3.954	4.063	4.174	4.289	4.406
130	4.525	4.647	4.772	4.900	5.031	5.165	5.302	5.442	5.585	5.732
140	5.881	6.034	6.190	6.330	6.513	6.680	6.850	7.024	7.202	7.384
150	7.569	7.759	7.952	8.150	8.351	8.557	8.767	, 8.981	9.200	9.424
160	9.652	9.885	10.12	10.36	10.61	10.86	11.12	11.38	11.65	11.92
170	12.20	12.48	12.77	13.07	13.37	13.67	13.98	14.30	14.62	14.96
180	15.29	15.63	15.98	16.34	16.70	17.07	17.44	17.82	18.21	18.61
190	10.01	19.42	19.84	20.27	20.70	21.14	21.50	22.05	22.52	22.99
200	23.47	23.96	24.46	24.97	25.48	26.00	26.53	27.07	27.62	28.18
210	28.75	29.33	29.92	30.52	31.13	31.75	32.38	33.02	33.67	34.33
220	35.00	35.68	36.37	37.07	37.78	38.50	39.24	39.99	40.75	41.52
230	42.31	43.11	43.92	44.74	45.57	46.41	47.37	48.14	49.03	49.93
240	50.84	51.76	52.70	53.65	54.62	55.60	56.60	57.61	58.63	59.67
250	60.72	61.79	62.88	63.98	65.10	66.23	67.38	68.54	69.72	70.92
260	72.13	74.36	74.61	75.88	77.17	78.46	79.78	81.11	82.46	83.83
270	85.22	86.63	88.06	89.51	90.97	92.45	93.96	95.49	97.03	98.61
280	100.2	101.8	103.4	105.0	106.7	108.4	110.1	111.8	113.6	115.4
290	117.2	119.0	120.8	122.7	124.6	126.5	128.4	130.4	132.4	134.4
300	136.4	138.5	140.6	142.7	144.8	147.0	149.2	151.4	153.6	155.9
310	158.2	160.5	162.8	165.2	167.6	170.0	172.5	175.0	177.5	180.0
320	182.6	185.2	187.8	190.4	193.1	195.8	198.5	201.3	204.1	206.9
330	209.8	212.7	215.6	218.6	221.6	224.6	227.7	230.8	233.9	237.1
340	240.3	243.5	246.8	250.1	253.4	256.7	260.1	263.6	267.1	270.6
350	274.1	277.7	281.3	284.9	288.6	292.3	296.1	299.9	303.8	307.7
360	311.6	315.5	319.5	323.5	327.6	331.7	335.9	340.1	344.4	348.7
370	353.0	357.4	361.8	366.2	370.7	375.2	379.8	384.4	389.1	393.8
380	398.6	403.4	408.2	413.1	418.1	423.1	428.1	433.1	438.2	443.4
390	448.6	453.9	459.2	464.6	470.0	475.5	481.0	486.2	492.2	497.9
400	503.6	509.3	515.1	521.0	526.9	532.9	538.9	545.0	551.1	557.3

Figure C-2. Vapor pressures of water at saturation (inches of Mercury)

The water vapor pressure existing in the gas-mixture passing the assembly may be determined from equations below,

(Eq.C-45)

$$e_a = e'' - \frac{(P_a - e'')\left[t_{dry(°F)} - t_{wet(°F)}\right]}{2800 - 1.3t_{wet(°F)}}$$

(The Carrier Equation)

If there is no leakage of gas, or condensation, upstream from the thermometer assembly the proportion (by volume) of water vapor in the duct at the sampling-point and in the assembly are equal. Therefore:

(Eq.C-46)

$$B_{ws} = \frac{e_a}{P_a}$$

b. To determine the water vapor pressure in a duct-gas for saturated conditions, substitute $\frac{e_s}{P_s}$ for B_{ws}.

(Eq.C-47)

$$e_s = \frac{e_a P_s}{P_a}$$

Condenser Method

a. Proportion of water vapor in a duct-gas.

When the water vapor content of the duct-gas is expected to be above 15%, the condenser method may be used. Care must be taken that no water vapor is condensed before the condenser. A filter is necessary to ensure that no particulate matter will foul the condenser, meter, or pump.

The gas leaving the condenser is saturated with water vapor, and if conditions are maintained so that the gas remains saturated as it passes through the meter, equation C-44 is applicable. The volume of water vapor that passed through the meter, referred to meter temperature and pressure, is:

(Eq.C-48)

$$V_{wm} = \left[\frac{e'_m}{P_m}\right] V_m$$

The total volume of water vapor in the sample extracted from the duct at the sampling-point, referred to meter temperature and pressure, is

(Eq.C-49)

$$V_{ws} = V_{wc} + V_{wm}$$

The proportion by volume of water existing in the duct at the sampling-point is

(Eq.C-50)
$$B_{ws} = \frac{V_{ws}}{V_{wc} + V_m}$$

Substituting for V_{ws} (see Equation C-49):

(Eq.C-51)
$$B_{ws} = \frac{V_{wc} + V_{wm}}{V_{wc} + V_m}$$

Water vapor pressure in a duct-gas. Having calculated B_{ws} from equation C-51, water vapor pressure existing in the duct at the sampling point may be determined by

(Eq. C-52)
$$e_s = B_{ws} P_s$$

DERIVATION OF RELATIVE HUMIDITY OF A DUCT-GAS

Definition

Relative humidity of the duct-gas at a sampling point is defined as:

(Eq. C-53)
$$\phi_s = \frac{e_s}{e'_s}$$

DETERMINATION OF RELATIVE HUMIDITY

Use of equations and table

e_s may be determined by measurement using the condenser method, or the wet- and dry-bulb temperature technique; e_s' may be found from saturation tables (Figure C-2). Equation C-57 may then be applied.

Use of a psychrometric chart

Psychrometric charts similar to Figures C-4 and C-5 may be used to determine relative humidity. Directions are shown in Figure C-3. Care should be taken that the pressure of the duct-gas is not so different from that for which the chart is designed to introduce significant error.

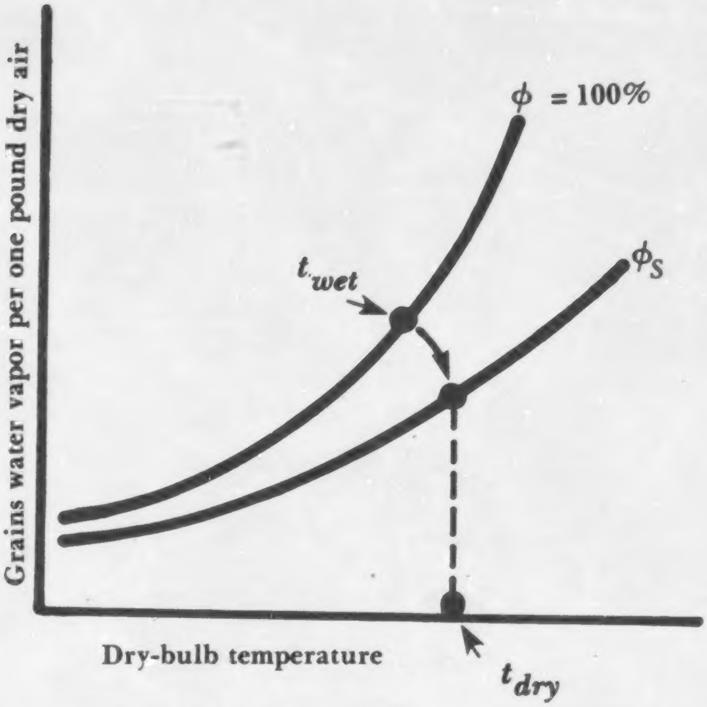

Grains water vapor per one pound dry air
ϕ = 100%
ϕ_S
t_{wet}
Dry-bulb temperature
t_{dry}

Figure C-3. Determination of relative humidity by using a psychrometric chart.

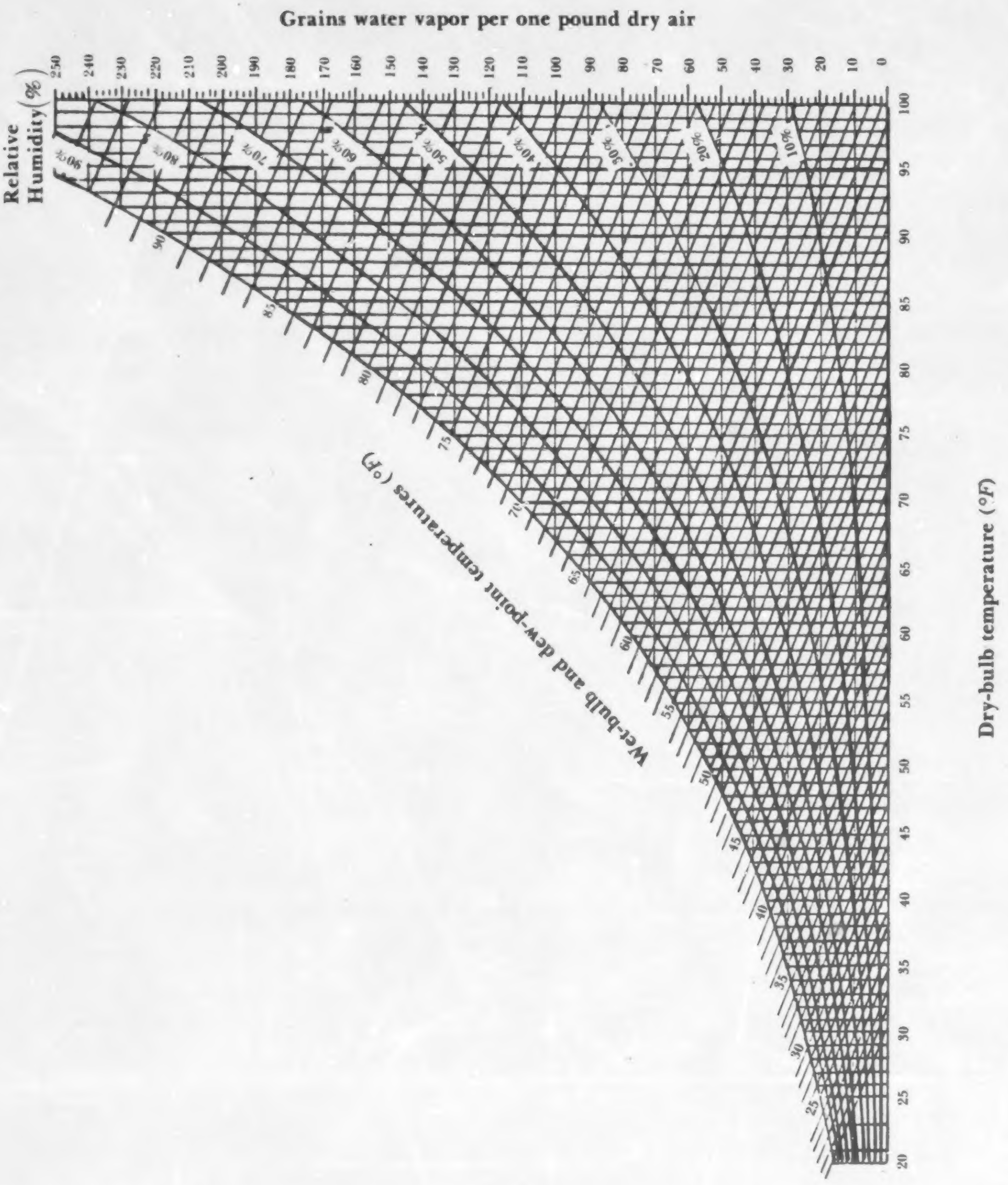


Figure C-4. Psychrometric chart for air at 20-100°*F* and barometric pressure of 29.92 in. Hg.

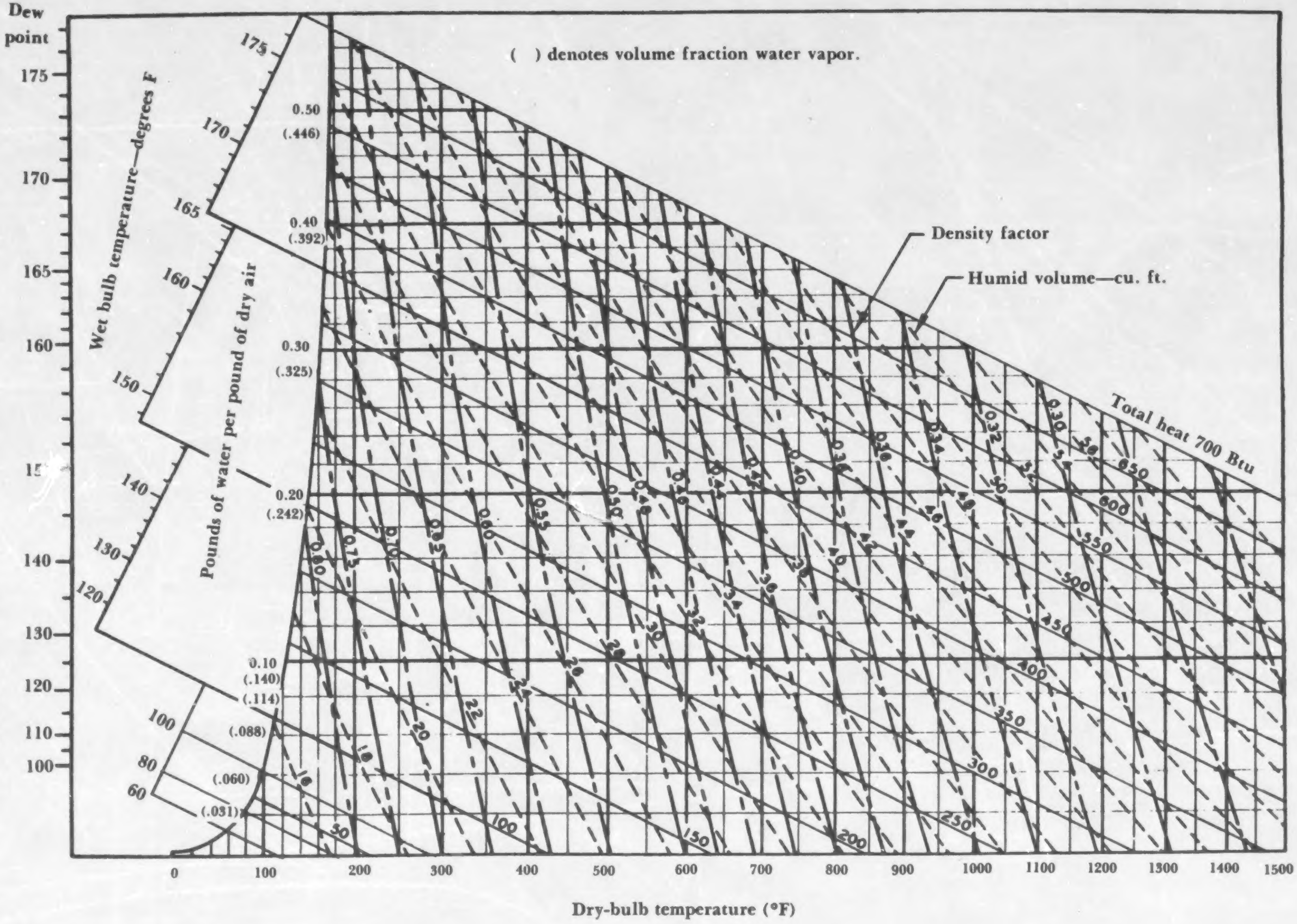


Figure C-5. Psychrometric chart for air at barometric pressure 29.92 in. Hg.

DETERMINATION OF PROPORTION OF WATER VAPOR

Since $B_{ws} = \frac{e_s}{P_s}$ the proportion (by volume) of water vapor in the duct-gas may be found by substituting $\phi_s(e_s')$ for e_p (see Equation C-51)

(Eq. C-54) $$B_{ws} = \frac{\phi_s e_s'}{P_s}$$

where

ϕ_s = *water vapor pressure in the duct-gas at the sampling point.*

e_s' = *water vapor pressure in the duct-gas for saturated conditions and dry-bulb temperature at the sampling point.*

P_s = *absolute pressure of the duct-gas at the sampling point.*

DEW-POINT

Definition

The temperature at which a mixture of gases can exist saturated with vapor is called the dew-point. Below the dew-point, condensations of water vapor occurs.

Determination of Dew-Point

1. Using saturation tables.

   The dew-point may be determined by use of water vapor pressure tables for saturation conditions as shown in Figure C-2. Knowing the existing water vapor pressure, the temperature at which the value exists can be interpolated from the table.

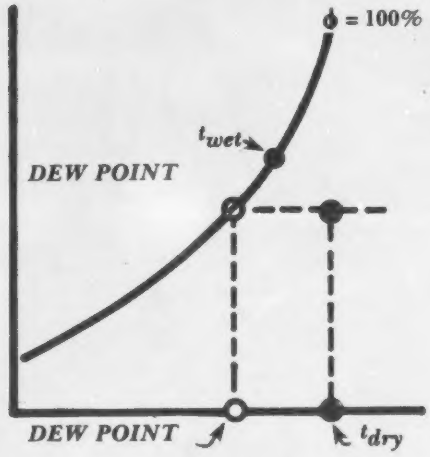


Figure C-6. Determination of Dew-Point by Use of a Psychrometric Chart.

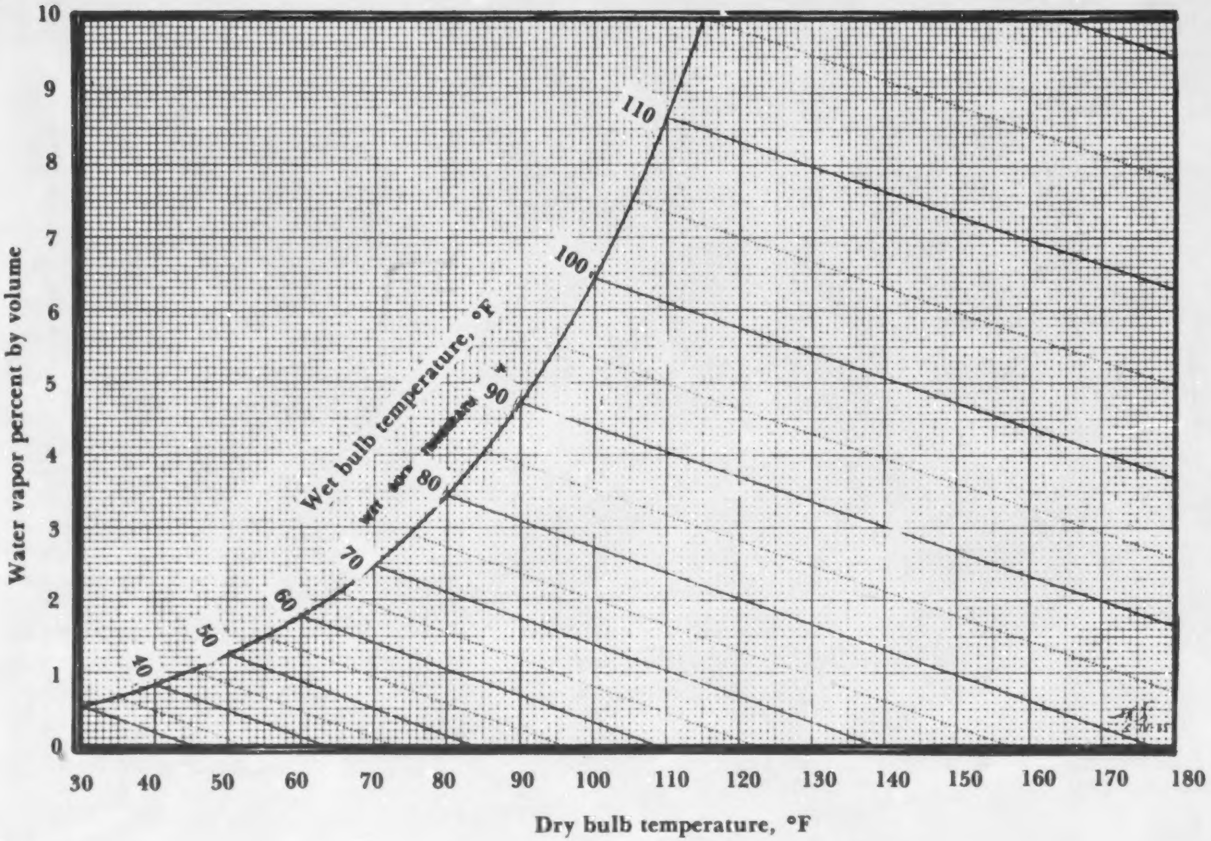


Figure C-7. Psychrometric chart expressing volume of water vapor by %.

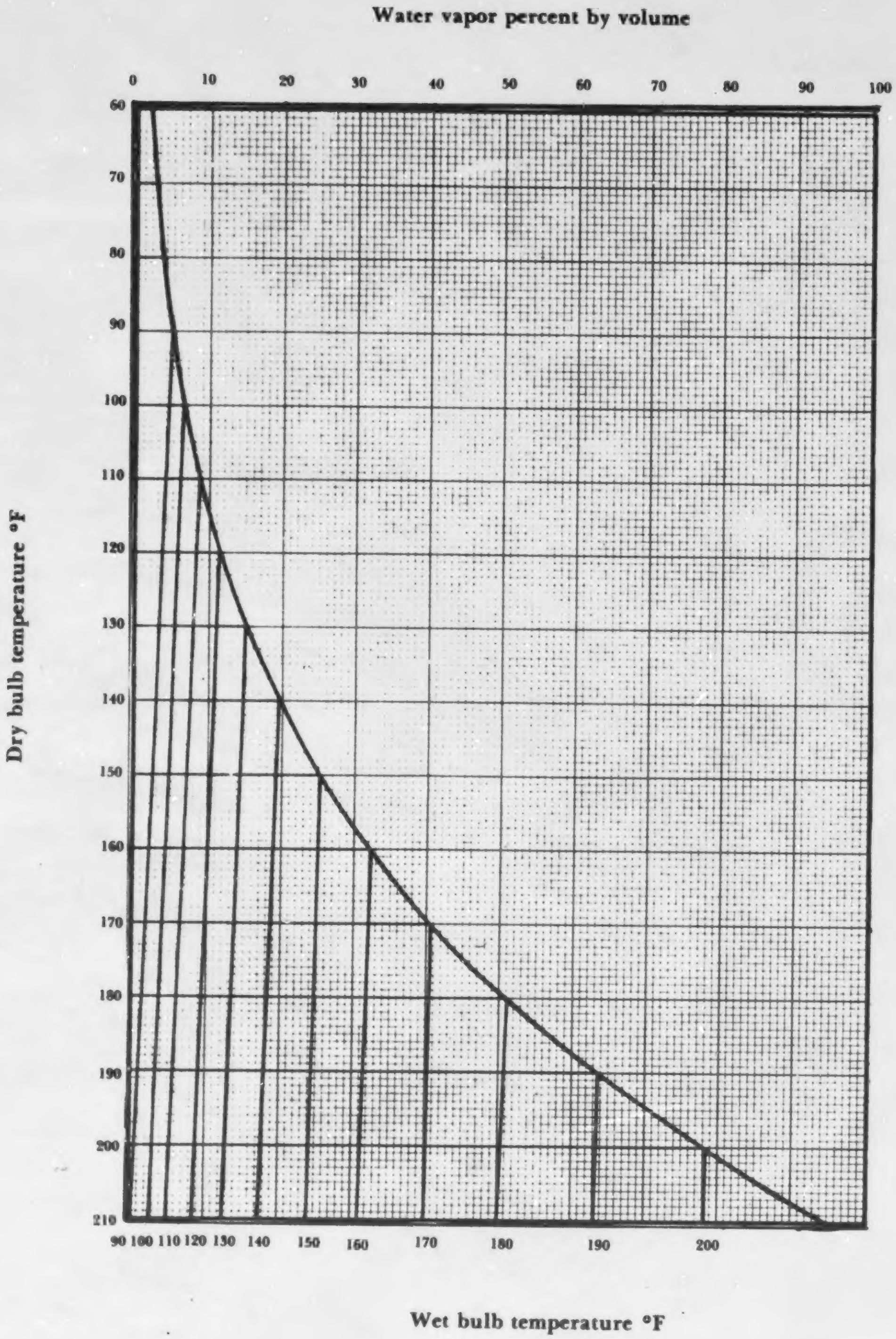


Figure C-8. High-temperature psychrometric chart for air-water vapor mixtures at 1 atm (29.921 in. Hg.).

2. Using a psychrometric chart.

   The dew-point may be determined from a psychrometric chart similar to Figures C-4 and C-5. Directions are shown in Figure C-6. Care should be taken that the pressure of the gas-mixture is not so different from that for which the chart is designed that significant error will be introduced.

DERIVATION OF THE EQUATION FOR MOLECULAR WEIGHT OF STACK GAS

Introduction

- Calculations involved in source sampling require knowledge of the molecular weight of a stack gas.
- Stack gas is almost always a mixture of gases.
- The apparent molecular weight of the gas mixture is a function of the composition of the mixture.
- Stack gas containing significant quantities of gaseous effluents other than oxygen, nitrogen, carbon dioxide, and water vapor should be analyzed chemically for composition and apparent molecular weight determined from this data.

Calculation of Apparent Molecular Weight of Gas Mixture

This derivation assumes the major components of the gases from a hydrocarbon combustion source to be oxygen, nitrogen, carbon dioxide, water vapor, and carbon monoxide.

The Ideal Gas Laws

1. Boyle's Law states that at constant temperature the volume of a given mass of a perfect gas of a given composition varies inversely with the absolute pressure.
2. Charles' Law states that at constant volume the absolute pressure of a given mass of a perfect gas of a given composition varies directly as the absolute temperature.
3. Combining these relationships into an equation, it may be stated

(Eq. C-55)

$$PV = \frac{mRT}{m}$$

where P = *absolute pressure*
T = *absolute temperature*
V = *volume of a gas*
M = *molecular weight of a gas (mass/mole)*
m = *massLof the gas*

4. Equation C-55 satisfies Dalton's Law of partial pressures when

(Eq. C-56) $$P_x V_{mixture} = \frac{m_x R T_{mixture}}{M_x}$$

where

P_x = *partial pressure of a gas component in a mixture of nonreacting gases.*
$V_{mixture}$ = *volume of the gas mixture*
m_x = *mass of a gas component*
R = *universal gas constant (in appropriate units)*
$T_{mixture}$ = *absolute temperature of the gas mixture*
M_x = *molecular weight (mass/mole) of a gas component*

Note $\frac{P_x V_{mixture}}{T_{mixture}}$ is constant only if $\frac{m_x}{M_x}$ remains constant.

Proportion by volume of a component in a gas mixture

1. Equation C-55 states that for a gas mixture

(Eq. C-57) $$P_{mix} V_{mix} = \frac{m_{mix} R T_{mix}}{M_{mix}}$$

2. Applying this relationship in equation C-56 and removing the common term

$$\frac{R T_{mix}}{V_{mix}}$$

it may be seen that the partial pressure of a given gas component is directly related to the mole fraction of that component in the gas mixture

(Eq. C-58) $$\frac{P_x}{P_{mix}} = \frac{\frac{m_x}{M_x}}{\frac{m_{mix}}{M_{mix}}}$$

3. At constant temperature and pressure equation C-55 may be written

(Eq. C-59) $$\frac{m}{M} = \frac{PV}{RT}$$

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4. Rearranging Equations C-56 and C-57 as Equation C-59 and substituting in Equation C-62

(Eq. C-60)

$$\frac{P_x}{P_{mix}} = \frac{V_x}{V_{mix}}$$

5. Letting the proportion by volume *(B_x)* equal $\frac{V_x}{V_{mix}}$. Equation C-60 may now be expressed

(Eq. C-61)

$$B_x = \frac{P_x}{P_{mix}}$$

6. Equation C-61 gives the proportion by volume of a gas component as a function of partial pressure, which (from Dalton's Law) is directly related to the mole fraction.

The apparent molecular weight of a gas mixture may now be derived using the relationship of partial pressure to mole fraction.

1. Rewriting Equation C-56

(Eq. C-62)

$$M_x P_x V_{mix} = m_x R T_{mix}$$

2. Dalton's Law tells us that Equation C-62 is actually

(Eq. C-63)

$$V_{mix} \Sigma P_x M_x = R T_{mix} \Sigma m_x$$

3. $\Sigma m_x = m_{mix}$ and from Equation C-56

(Eq. C-64)

$$m_{mix} = \frac{P_{mix} V_{mix} M_{mix}}{R T_{mix}}$$

4. Substituting for Σm_x and solving for M_{mix} in Equation C-64 becomes

(Eq. C-65)

$$M_{mix} = \frac{\Sigma P_x M_x}{P_{mix}}$$

5. Since $\frac{P_x}{P_{mix}} = B_x$, Equation C-65 can be

(Eq. C-66)

$$M_{mix} = \Sigma B_x M_x$$

Stack Gas Analysis Using Orsat Analyzer.

1. Orsat operates at constant proportion by volume of H_2O vapor
2. Yield volume data on dry basis (volume related to mole fraction and partial pressure)
3. Apparent molecular weight must include H_2O vapor component of stack gas
4. Stack gas moisture content may be obtained as described in moisture content section
5. Actual apparent molecular weight may be calculated by

$$M_{mix} = \Sigma B_x M_x (1 - B_{ws}) + B_{ws} M_{H_2O}$$

$\Sigma B_x M_x = sum\ of\ dry\ mole\ fractions$

$B_{ws} = proportion\ by\ volume\ of\ H_2O\ in\ stack\ gas$

$M_{H_2O} = molecular\ weight\ of\ H_2O$

APPENDIX D. CONCENTRATION CORRECTION EQUATIONS

Introduction

After a value for the concentration of a pollutant in a flue gas stream is obtained by a reference method test, it is often necessary to correct the value to some standard set of conditions, which is done to compare the data from one source to that of another. Different stack temperatures and different amounts of excess air would make a comparison of the *actual* concentrations almost meaningless. Therefore, terms such as SCFM for "Standard Cubic Feet per Minute" instead of ACFM ("Actual Cubic Feet per Minute") and c_s (corr. 50% EA) instead of c_s are generally used when reporting data. Note that in reporting data in units of the standard, E (lbs./10^6 Btu heat input), the pollutant concentration is expressed as pounds per dry *standard* cubic foot and an excess air correction is included in the F factor equation (Chapter 7). In this section, derivations for correcting a concentration to standard conditions, 50% excess air, 12% CO_2, and 6% O_2 will be given.

Concentration Corrected to Standard Conditions

A concentration is expressed as weight per volume or lb./ft.^{3}.

(Eq.D-1)

$$c_s = \frac{m}{V}$$

The volume of gas passing through the nozzle will be at stack pressure and temperature. After going through the Method 5 train and meter, that temperature and pressure will change. A reference or standard set of conditions must be used, therefore, to make the data meaningful. The ideal gas law is used in these considerations (see Chapter 2).

Therefore, since

(Eq.D-2)

$$PV = nRT$$

$$V_{stack} = \frac{nRT_{stack}}{P_{stack}} \quad and \quad \begin{matrix} V_{corr.\ to} \\ standard \\ conditions \end{matrix} = \frac{nRT_{std}}{P_{std}}$$

For the same number of moles of gas, the volume that that number would occupy at standard conditions would be as follows

dividing,

(Eq.D-3)

$$\frac{V_{corr}}{V_s} = \frac{\dfrac{nRT_{std}}{P_{std}}}{\dfrac{nR\ T_s}{P_s}} = \frac{T_{std}\ P_s}{T_s\ P_{std}}$$

or $$V_{corr} = V_s \frac{T_{std}\ P_s}{T_s\ P_{std}}$$

and $$c_s \textit{ (at standard conditions)} = \frac{m}{V_{corr}} = \frac{m}{V_s}\ \frac{T_s\ P_{std}}{T_{std}\ P_s}$$

$$c_{s\,corr} = c_s \frac{T_s\ P_{std}}{T_{std}\ P_s}$$

EPA has defined $T_{std} = 460 + 68°F$ and $P_{std} = 29.92$ inches Hg (42 FR 41754, August 18, 1977).

To report a concentration on a dry basis, the volume must be expressed as if all of the water had been removed. The value of B_{ws} must be known in this case.

(Eq.D-4) $$V_{dry} = V_{wet} - V_{wet}B_{ws}$$

$$V_{dry} = V_{wet}(1 - B_{ws})$$

or $$c_{s\,(dry)} = \frac{m}{V_{dry}} = \frac{m}{V_{wet}\ (1 - B_{ws})}$$

$$c_{s\,(dry)} = \frac{C_{s(wet)}}{(1 - B_{ws})}$$

Combining these two corrections,

(Eq.D-5) $$c_s \textit{ (corrected to lbs./DSCF)} = \frac{c_{s(wet)}}{(1 - B_{ws})}\ \frac{T_s\ P_{std}}{T_{std}\ P_s}$$

Excess Air

Several types of concentration corrections have been devised based on the combustion characteristics of fossil fuels. Excess air is defined as that percentage of air added in excess of that required to just combust a given amount of fuel. Normally, to achieve efficient fuel combustion, more air is needed than the stoichiometric amount, i.e., one carbon atom to two oxygen molecules. (Details of these combustion conditions are given in APTI course #427.)

Depending on the amount of excess air, different concentrations of CO_2 and oxygen in the stack gas will result, as shown in Figure D-1.

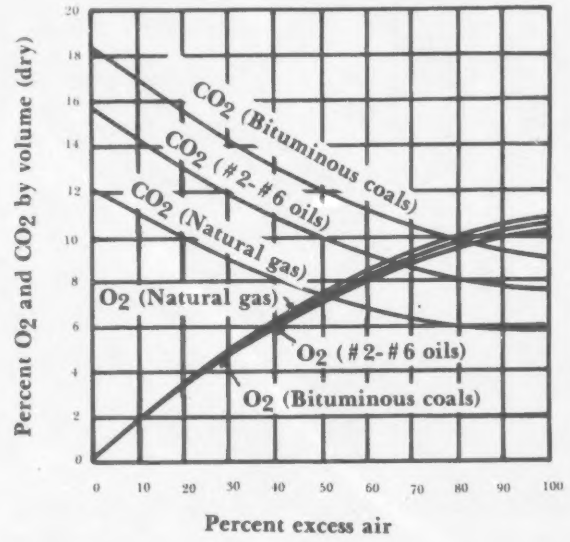

Figure D-1. Concentrations of CO_2 and O_2 in stack by amount of excess air.

Since the concentration of the pollutants produced in the source could be reduced by adding more excess air, (i.e., if $c_s = m/V$, if V is increased with m constant, c_s would decrease), it has been found necessary in some cases to correct to a given excess air condition. A value of 50% excess air has been chosen as a reference condition since at one time many boilers operated at this condition. Note also that if such a correction is made, that it will account for dilution caused by air leaking in at the preheater or other duct work.

The expression for % excess air, as given in EPA Method 3, is

$$\text{(Eq.D-6)} \qquad \%EA = \frac{\%O_2 - 0.5\%\ CO}{0.264\%\ N_2 - (\%O_2 - 0.5\%\ CO)}\ 100$$

To derive this expression, gas volumes associated with the combustion of the fuel must be considered.

$$\text{(Eq.D-7)} \qquad \underbrace{V_{Theoretical}}_{\substack{\text{stoichiometric volume}\\ \text{of air required to}\\ \text{consume an amount of}\\ \text{fuel}}} = \underbrace{V_{Total}}_{\substack{\text{total volume}\\ \text{of air used}}} - \underbrace{V_{EA}}_{\substack{\text{volume of air}\\ \text{in excess of}\\ V_{Theoretical}}}$$

Since air is composed of 79% N_2 and 21% O_2, if there was complete stoichiometric combustion, all of the oxygen would be consumed and

(Eq.D-8)

$$V_{N_2} = 0.79\ V_{Theoretical}$$

$$V_{Theoretical} = \frac{V_{N_2}}{0.79}$$

Remember, however, that when excess air is added, the oxygen contained in that volume will not react since there will be no carbon left to consume it,

or

(Eq.D-9)

$$V_{O_2}\ (remaining) = 0.21\ \ V_{EA}$$

The problem of incomplete combustion must also be considered in this calculation. Carbon monoxide is produced if burning conditions are not adequate.

$$C + O_2 \xrightarrow{\qquad} CO + \tfrac{1}{2}\ O_2$$

The amount of oxygen remaining in the flue gas must then be corrected for incomplete combustion since for each two molecules of CO produced, one molecule of oxygen will result,

(Eq.D-10)

$$0.5\ \ V_{CO} = V_{O_2}\ (incomplete\ combustion)$$

Equation D-8 must be modified so that

(Eq.D-11)

$$V_{O_2}(remaining) = 0.21\ \ V_{EA} + 0.5\ \ V_{CO}$$

(Looking at this another way, ½ of an oxygen molecule is released for each CO molecule and would contribute to V_{O_2} (remaining).) Therefore, from Equation D-11

(Eq.D-12)

$$V_{EA} = \frac{V_{O_2} - 0.5\ V_{CO}}{0.21}$$

Substituting Equations D-8 and D-12 into Equation D-7, we have

(Eq.D-13)

$$V_{Theoretical} = V_T - V_{EA}$$

$$V_{Theoretical} = \frac{V_{N_2}}{0.79} - \frac{(V_{O_2} - 0.5\ V_{CO})}{0.21}$$

Percent excess air is defined as that percent of air in excess of that needed for complete combustion, or

(Eq.D-14)

$$\%EA = \frac{V_{EA}}{V_{Theoretical}} \times 100$$

Therefore:

(Eq.D-15)

$$\%EA = \frac{\dfrac{V_{O_2} - 0.5V_{CO}}{0.21}}{\dfrac{V_{N2}}{0.79} - \dfrac{V_{O_2} - 0.5V_{CO}}{0.21}} \times 100$$

$$\%EA = \frac{V_{O_2} - 0.5\ V_{CO}}{0.266\ V_{N_2} - V_{O_2} + 0.5\ V_{CO}} \times 100$$

divide numerator and denominator by V_T

$$\%EA = \frac{V_{O_2}/V_T - 0.5V_{CO}/V_T}{0.266\ V_{N_2}/V_T - V_{O_2}/V_T + 0.5\ V_{CO}/V_T} \times 100$$

$$\%EA = \frac{\%O_2 - 0.5\ \%\ CO}{0.266\ \%\ N_2 - \%\ O_2 + 0.5\ \%\ CO}$$

Concentration Corrected to 50% Excess Air

To correct a pollutant concentration to 50% Excess Air

(Eq.D-16)

$$\frac{V_{EA} \pm \Delta V}{V_{Theoretical}} \times 100 = 50\%\ EA$$

where ΔV is the volume that would have to be added or subtracted to give 50% EA.

$$\Delta V = V_{EA} \pm 0.5\ V_{Theor}$$

and

$$F_{EA}\ V_T = V_T \pm \Delta V$$

where F_{EA} is the proportion of V_T that would have to be changed to give 50% EA.

$$F_{EA} = \frac{V_T \pm \Delta V}{V_T} = \frac{V_{Theor} + V_{EA} - V_{EA} + 0.5 V_{Theor}}{V_{Theor} + V_{EA}}$$

$$= \frac{1.5 \ V_{Theor}}{V_{Theor} + V_{EA}}$$

divide numerator and denominator by V_{Theor} to give

(Eq.D-17)

$$F_{EA} = \frac{1.5}{1 + \dfrac{V_{EA}}{V_{Theor}}} = \frac{150}{100 + \% \ EA}$$

Therefore, since

$$c_S = \frac{m}{V_T}$$

$$c_S \ (corrected \ 50\% \ EA) = \frac{m}{V_T \ F_{EA}} = \frac{m}{V_T \left(\dfrac{150}{100 + \ \%EA} \right)}$$

(Eq.D-18)

$$c_S \ (corr) = c_S \left(\frac{100 + \%EA}{150} \right)$$

It should be noted that there is a method of calculating c_S corrected to 50% EA without first calculating % EA.

Starting from

(Eq.D-19)

$$F_{EA} = \frac{V_T \pm \Delta V}{V_T} = 1 - \frac{(V_{EA} - 0.5 V_{th})}{V_T}$$

$$F_{EA} = 1 - \left(\frac{V_{EA} - 0.5 \ (V_T - V_{EA})}{V_T} \right)$$

$$= 1 - \left(\frac{1.5 V_{EA} - 0.5 V_T}{V_T} \right)$$

from Equations D-8 and D-12, we have

$$= 1 - \left[\frac{1.5(V_{O_2} - 0.5\ V_{CO}) - 0.5\left(\frac{V_{N_2}}{0.79}\right)}{V_T} \right]$$

$$= 1 - \frac{1.5\%O_2 - 0.75\%CO - 0.133\%\ N_2}{0.21}$$

and

(Eq.D-20)

$$c_s\,(corr) = \frac{m}{V_T\ F_{EA}} = c_s \frac{1}{1 - \left[\frac{1.5\%\ O_2 - 0.75\%\ CO - 0.133\%\ N_2}{21} \right]}$$

It should be noted that equations D-18 and D-19 are not equivalent and cannot be made equivalent. They do, however, give the same answers using values characteristic of combustion sources. Note that Equation D-14 for $\%EA$ becomes discontinuous as the flue gas approaches a composition corresponding to that of air (neglecting CO). Equation D-18 also becomes discontinuous under certain conditions (e.g., $\%O_2 = 7.7\%$, $\%N_2 = 79$, $\%\ CO = 0$).

Correcting Concentration to 12% CO_2

The derivations for correcting a concentration to 12% CO_2 or 6% O_2 are similar to that for the 50% Excess Air Correction. For a correction to 12% CO_2 in the flue gas.

(Eq.D-21)

$$\frac{V_{CO_2}}{V_T \pm \Delta V} = 0.12$$

or

$$F_{CO_2}\ V_T = V_T \pm\ \Delta V$$

where ΔV = amount of air added or subtracted to give 12% CO_2 and F_{CO_2} is the fraction by which V_{actual} would have to be reduced or increased to do this.

Substituting,

(Eq.D-22)

$$\frac{V_{CO_2}}{F_{CO_2}\ V_T} = 0.12$$

and

(Eq.D-23)

$$F_{CO_2} = \frac{\%CO_2}{12}$$

$$c_{s12\,\%\,CO_2} = \frac{m}{V_T F_{CO_2}} = \frac{c_s}{F_{CO_2}}$$

$$c_{s12\%} = \frac{12}{\%CO_2}\, c_s$$

Correcting Concentration to 6% O_2

Instead of correcting a concentration to 12% O_2, a correction may be made using just the oxygen concentration. The oxygen correction is somewhat more complicated than that for CO_2 since dilution air will contain oxygen.

The derivation begins with

(Eq.D-24)

$$\frac{V_{O_2} \pm 0.21\ \Delta V}{V_T \pm \Delta V} = 0.06$$

where V is the amount of air added or subtracted to give 6% O_2 in the corrected volume. Note that the term ±0.21 ΔV is due to the oxygen contained in air.

For F_{O_2} being the fractional amount, V_T must be changed,

(Eq.D-25)

$$F_{O2} V_T = V_T - \Delta V$$

and substituting into Equation D-22

$$\frac{V_{O_2} + 0.21\ V_T - 0.21\ V_T \pm 0.21\ \Delta V}{V_T + \Delta V} = .06$$

$$\frac{V_{O_2} - 0.21\ V_T + 0.21\ F_{O_2} V_T}{F_{O_2} V_T} = .06$$

$$V_{O_2} - 0.21\ V_T = 0.15\ F_{O_2}\ V_T$$

and

(Eq.D-26)

$$F_{O_2} = 0.21\ V_T - V_{O_2} = \frac{21 - \%O_2}{15}$$

and similarly to the previous derivations

(Eq.D-27)

$$c_s(6\%\ O_2) = \frac{15\ c_s}{21 - \%\ O_2}$$

Note that if a correction to 3% O_2 was needed

(Eq.D-28)

$$c_s(3\%\ O_2) = \frac{18\ c_s}{21 - \%\ O_2}$$

APPENDIX E. INTERNATIONAL METRIC SYSTEM

Systeme International d'Unites (SI Units)

Base Units of the International Metric System (SI)

Quantity	Name of the Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Luminous intensity	candela	cd
Amount of substance	mole	mol

Recommended Decimal Multiples and Submultiples and the Corresponding Prefixes and Names

Factor	Prefix	Symbol	Meaning
10^{12}	tera	T	One trillion times
10^{9}	giga	G	One billion times
10^{6}	mega	M	One million times
10^{3}	kilo	k	One thousand times
10^{2}	hecto	h	One hundred times
10	deca	da	Ten times
10^{-1}	deci	d	One tenth of
10^{-2}	centi	c	One hundredth of
10^{-3}	milli	m	One thousandth of
10^{-6}	micro	μ	One millionth of
10^{-9}	nano	n	One billionth of
10^{-12}	pico	p	One trillionth of
10^{-15}	femto	f	One quadrillionth of
10^{-18}	atto	a	One quintillionth of

Some Derived Units of the International Metric System (SI)

Quantity	Name of the unit	Symbol	Equivalence
Frequency	hertz	Hz	1 Hz = 1 s^{-1}
Force	newton	N	1 N = 1 kg-m/s
Pressure	pascal	Pa	1 Pa = 1 N/m
Energy	joule	J	1 J = 1 N-m
Power	watt	W	1 W = 1 J/s
Quantity of electricity	coulomb	C	1 C = 1 A-s
Electrical potential or electromotive force	volt	V	1 V = 1 W/A
Electric resistance	ohm	Ω	1 Ω = 1 V/A
Electric conductance	siemens	S	1 S = A/V
Electric capacitance	farad	F	1 F = 1 C/V
Magnetic flux	weber	Wb	1 Wb = 1 V-s
Magnetic flux density	tesla	T	1 T = 1 Wb/m
Inductance	henry	H	1 H = 1 Wb/A
Luminous flux	lumen	ℓm	1 ℓm = 1 cd-sr
Illumination	lux	ℓx	1 ℓx = 1 ℓx/m

Some Suggested SI Units for Air Pollution Control

Volume flow: Liters per second (l/s)
Velocity (gas flow): Meters per second (m/s)
Air to cloth ratio: Millimeters per second (mm/s)
Pressure: Kilopascals (kPa)

APPENDIX F. CONVERSION TABLES

Conversion Between Different Units

Listed below are quantities of the English and engineering systems of units that are commonly found in the literature on air pollution. Our intention is to present them so that their equivalent in the MKS system of units can be found quickly. Quantities that are listed in each horizontal line are equivalent. The quantity in the middle column indicates the simplest definition or a useful equivalent of the respective quantity in the first column.

1 acre	1/640 mi^{2}	4.047 X 10^{3} m^{2}
1 Angstrom (Å)	10^{-8} cm	10^{-10} m
1 atmosphere (atm)	1.013 X 10^{6} dyn/cm^{2}	1.013 X 10^{5} N/m^{2}
1 bar (b)	10^{6} dyn/cm^{2}	10^{5} N/m^{2}
1 barrel (bbl)	42 gal, U.S.A.	0.159 m^{3}
1 boiler horsepower	3.35 X 10^{4} Btu/hour	9.810 X 10^{3} W
1 British Thermal Unit (Btu)	252 cal	1.054 X 10^{3} J
1 Btu/hour	1.93 X 10^{6} erg/sec	0.293 W
1 calorie (cal)	4.184 X 10^{-7} erg	4.184 J
1 centimeter of mercury (cm Hg)	1.333 X 10^{4} dyn/cm^{2}	1.333 X 10^{3} N/m^{2}
1 cubic foot, U.S.A. (cu ft)	2.832 X 10^{4} cm^{3}	2.832 X 10^{-2} m^{3}
1 dyne (dyn)	1 g-cm/sec^{2}	10^{-5} N
1 erg	1 g-cm^{2}/sec^{2}	10^{-7} J
1 foot, U.S.A. (ft)	30.48 cm	0.3048 m
1 foot per minute (ft/min)	1.829 X 10^{-2} km/hr	5.080 X 10^{-3} m/sec
1 gallon, U.S.A. (gal)	3.785 X 10^{3} cm^{3}	3.785 X 10^{-3} m^{3}

Conversion Factors

Capacity, Energy, Force, Heat

Multiply	By	To Obtain
Btu	0.252	Kilogram-calories
Btu	9.48×10^{-4}	Watt-seconds (Joules)
Btu/min	3.927×10^{-4}	Horsepower-hours
Btu/min	2.928×10^{-4}	Kilowatt-hours
Btu/min	0.02356	Horsepower
Btu/min	0.01757	Kilowatts
Btu/min	10^{-3}	Pound/hour steam
Horsepower (boiler)	33,479	Btu/hour
Horsepower (boiler)	9.803	Kilowatts
Horsepower-hours	0.7457	Kilowatt-hours
Kilowatts	56.92	Btu/minute
Kilowatts	1.341	Horsepower
Kilowatt-hours	3415	Btu
Kilowatt-hours	1.341	Horsepower-hours
Megawatts	1360	Kilogram/hour steam
Pound/hr steam	0.454	Kilogram/hour

Heat Transfer Coefficient

Multiply	By	To Obtain
Btu/(hr)(ft^2)(°F)	0.001355	Cal/(sec)(cm^2)(°C)
	1.929×10^6	Btu/(sec)(in^2)(°F)
	0.0005669	Watts/(cm^2)(°C)

Flow

Multiply	By	To Obtain
Cubic feet/minute	0.1247	Gallons/second
Cubic feet/second	0.646317	Million gallons/day
Cubic feet/second	448.831	Gallons/minute
Cubic meter/second	22.8	Million gallons/day
Cubic meter/second	8.32×10^{9}	Gallons/year
Gallons/year	10.37×10^{-6}	Cubic meters/day
Gallons/minute	2.228×10^{-3}	Cubic feet/second
Liters/minute	5.886×10^{-4}	Cubic feet/second
Liters/minute	4.403×10^{-3}	Gallons/second
Million gallons/day	1.54723	Cubic feet/second
Million gallons/day	0.044	Cubic meters/second
Million gallons/day	695	Gallons/minute
Pounds of water/minute	2.679×10^{-4}	Cubic feet second

Length, Area, Volume

Multiply	By	To Obtain
Acres	43,560	Square feet
Acres	4047	Square meters
Acres	1.562×10^{-3}	Square miles
Barrels-oil	0.156	Cubic meters
Barrels-oil	42	Gallons-oil
Centimeters	0.3937	Inches
Cubic feet	2.832×10^{4}	Cubic centimeters
Cubic feet	1728	Cubic inches
Cubic feet	0.02832	Cubic meters
Cubic feet	0.03704	Cubic yards
Cubic feet	7.48052	Gallons
Cubic feet	28.2	Liters
Cubic meters	35.31	Cubic feet
Cubic meters	264.2	Gallons
Feet	30.48	Centimeters
Feet	0.3048	Meters

Length, Area, Volume cont'd

Multiply	By	To Obtain
Gallons	0.1337	Cubic feet
Gallons	3.785×10^{-3}	Cubic meters
Gallons, Imperial	1.20095	U.S. gallons
Gallons water	8.3453	Pounds of water
Liters	0.2642	Gallons
Meters	3.281	Feet
Meters	39.37	Inches
Square feet	2.296×10^{-5}	Acres
Square feet	0.09290	Square meters
Square meters	2.471×10^{-4}	Acres
Square meters	10.76	Square feet
Square miles	640	Acres

Mass, Pressure, Temperature, Concentration

Multiply	By	To Obtain
Atmospheres	29.92	Inches of mercury
Atmospheres	33.90	Feet of water
Atmospheres	14.70	Pounds/Square inch
Feet of water	0.02947	Atmospheres
	0.04335	Pounds/square inch
	62.378	Pounds/square foot
Inches of Hg	0.03342	Atmospheres
	13.60	Inches of water
	1.133	Feet of water
	0.4912	Pounds/square inch
	70.727	Pounds/square foot
	345.32	Kilograms/square meter
Inches of water	0.03609	Pounds/square inch
	5.1981	Pounds/square foot
	25.38	Kilograms/square meter

Mass, Pressure, Temperature, Concentration cont'd

Multiply	By	To Obtain
Kilograms/square centimeter	0.9678	Atmospheres
	14.22	Pounds/square foot
Kilograms/square meter	0.00142	Pounds/square inch
	0.20482	Pounds/square foot
	0.00328	Feet of water
	0.1	Grams/cm^2
Kilograms	2.2046	Pounds
Pounds	453.5924	Grams
Pounds of water	0.01602	Cubic feet
Pounds of water	0.1198	Gallons
Pounds/square inch	0.06804	Atmospheres
Pounds/square inch	2.307	Feet of water
Pounds/square inch	70.31	Grams/cm^2
Pounds/square inch	2.036	Inches of mercury
Temp.(°*C*) + 17.78	1.8	Temperature(°*F*)
Temp.(°*F*) − 32	0.555	Temperature(°*C*)

Degrees Kelvin = degrees Centigrade + 273.16
Degrees Rankin = degrees Fahrenheit + 459.69

Multiply	By	To Obtain
Tons (metric)	2205	Pounds
Tons (short)	0.89287	Tons (long)
Tons (short)	0.9975	Tons (metric)

Thermal Conductivity

Multiply	By	To Obtain
Btu/(hr)(ft^2)(°*F*/ft)	0.00413	Cal/(sec)(cm^2)(°*C*/cm)
	12	Btu/(hr)(ft^2)(°*F*/in)

Viscosity

Multiply	By	To Obtain
Poise	1.0	Gm/cm sec
	1.0	Dyne sec/cm^2
	100	Centipoise
Centipoise	0.000672	Pounds/foot second
	0.0000209	Pound/second square foot
	2.42	Pound/foot hour
Stoke	1.0	Square centimeter/second
	0.155	Squared inch/second
	0.001076	Squared foot/second
	density (gm/cm^3)	Poise

Density

Multiply	By	To Obtain
Grams per cc	62.428	Pounds/cubic feet
	0.03613	Pounds/cubic inch
	8.345	Pounds/U.S. gallon
Gram-moles of Ideal Gas at 0°*C* and 760mm Hg.	22.4140	Liters
Pounds per cubic inch	1728	Pounds/cubic feet
	27.68	Grams/cubic centimeter
Pound-moles of Ideal Gas at 0°*C* and 760 mm Hg.	359.05	Cubic feet
Grams/liter	58.417	Grains/gallons
Grams/liter	8.345	Pounds/1000 gallons
Grams/liter	0.062427	Pounds/cubic feet
Parts/million	0.0584	Grains/U.S. gallons
Parts/million	8.345	Pounds/million gallons

Conversion from ppm to g/m^3 at STP

$$T_{std} = 273.15\,°K$$

$$P_{std} = 1\ atm$$

(Eq. F-1.) $$\frac{g}{dscm} = \frac{ppm \times M\left(\frac{g}{g\text{-}mole}\right)}{22.414\,\frac{liters}{g\text{-}mole} \times 10^3\,\frac{M^3}{liter}\left(\frac{293.15\,°K}{273.15\,°K}\right)} \times \frac{1}{1 \times 10^6 ppm}$$

APPENDIX G. CONSTANTS AND USEFUL INFORMATION

Energy Equivalences of Various Fuels

Approximate Values

Bituminous coal	– 22×10^6 Btu/ton
Anthracite coal	– 26×10^6 Btu/ton
Lignite coal	– 16×10^6
Residual oil	–147,000 Btu/gal
Distillate oil	140,000 Btu/gal
Natural gas	1,000 Btu/ft^3

1 lb of water evaporated from and at 212°*F* equals:

0.2844 Kilowatt-hours
0.3814 Horsepower-hours
970.2 Btu

1 cubic ft air weighs 34.11 gm.

Miscellaneous Physical Constants

Avogadro's Number	6.0228×10^{23}	Molecules/gm mole
Gas-Law Constant R	1.987	Cal/(gm mole)(°K)
	1.987	Btu/(lb mole)(°R)
	82.06	(cm^3)(atm)/(gm mole)(°K)
	10.731	(ft^3)(lb)(in.^{2})/(lb mole)(°R)
	0.7302	(ft^3)(atm)/(lb mole)(°*R*)

Weight of O_2, N_2 and Air

		Pounds	Tons	SCF Gas
1 Pound	Oxygen			
	Nitrogen	1.0	0.0005	12.08
1 Ton	Oxygen			
	Nitrogen	2000.0	1.0	24,160
				27,605
1 SCF Gas	Oxygen	0.08281	0.00004141	
	Nitrogen	0.07245	0.00003623	1.0

Typical Coal Combustion Emissions Data

Particulate mass loading, after precipitator	0.03-3.0 gm/cu meter
before precipitator	0.2-12 gm/cu meter
Mass loading spatial variation at duct cross-section	±50%
Particle size, after precipitator	Mass median diameter ≅5µm
before precipitator	95% <25µm (by mass)
Extreme particle size range	0.01-300 µm
Flue gas velocity	Average: 15-20 m/sec. Range: 10-40 m/sec.
Flue gas temperature	Typical: 140-165°C Range: 130-205°C
Dew point	Acid: 105-130°C Water: <60°C
Moisture content of gas	5-10% by volume
Static pressure at sample ports	Range: 15 cm positive to 35 cm negative water pressure
Turbulent Flow fluctuations	30-120 cycles per minute
Traversing distance across duct from port	Typical: 2-5 meters Range: 1.5-10 meters

Typical Oil Combustion Emissions Data

Particulate mass loading, uncontrolled	Typical: 0.06-0.2 gm/cu meter Range: 0.015-1.0 gm/cu meter
Mass loading variation with time	As much as 10-fold increase over typical
Mass loading variation during soot blowing	About 4-fold increase over typical
Particle size	Typical: 0.01-1.0µm Range: <0.01-40 µm
Flue gas temperature range	120-165°C
Flow conditions	Similar to those for coal combustion

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16. ABSTRACT

This manual is used in conjunction with Course #450, "Source Sampling for Particulate Pollutants", as designed and presented by the EPA Air Pollution Training Institute (APTI). The manual supplements the course lecture material, presenting detailed discussions in an introductory manner on the following topics:

- Basic Definitions for Source Sampling
- Basic Concepts of Gases
- The EPA Method 5 Sampling Train
- The EPA Method 5 Source Test
- Calibration Procedures
- Source Sampling Calculations
- Report Writing
- Error Analysis
- F-factor Methods
- Particle Sizing
- Opacity Monitoring

Derivations are given for many of the basic source sampling equations. The manual, when used with the student workbook, EPA-450/2-79-007, during the lecture and laboratory sessions of Course #450, provides comprehensive instruction in the performance of EPA reference method 5.

(NOTE: There is also an Instructor's manual that may be used in conducting the training course - - EPA-450/2-80-003, APTI Course #450, Source Sampling for Particulate Pollutants - Instructor's Guide.)

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
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Collection	Particle Measurement	14D
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Dust		
Calibrating		
Filtered Particle Sampling		

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